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METHOD OF AND SYSTEM FOR PRODUCING DIGITAL IMAGES OF OBJECTS WITH SUBTANTIALLY REDUCED SPECKLE-NOISE PATTERNS BY ILLUMINATING SAID OBJECTS WITH SPATIALLY AND/OR TEMPORALLY COHERENT-REDUCED PLANAR LASER ILLUMINATION

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CROSS-REFERENCE TO RELATED U.S. APPLICATIONS

This is a Continuation-in-Part of: copending Application Serial No. 09/781,665 "Method Of And System For Acquiring And Analyzing Information About The Physical Attributes Of Objects Using Planar Laser Illumination Beams, Velocity-Driven Auto-Focusing And Auto-Zoom Imaging Optics, And Height And Velocity Controlled Image Detection Arrays" filed February 12, 2001; copending Application Serial No. 09/780,027 entitled "Method Of And System For Producing Images Of Objects Using Planar Laser Illumination Beams And Image Detection Arrays" filed February 9, 2001 under 37 C.F.R. 1.10 (Express Mail No. EL701906489US); copending Application Serial No. 09/721,885 filed November 24, 2000; International Application PCT/US99/06505 filed March 24, 1999, published as WIPO WO 99/49411; International Application PCT/US99/28530 filed December 2, 1999, published as WIPO Publication WO 00/33239; International Application PCT/US00/15624 filed June 7, 2000, published as WIPO Publication WO 00/75856; copending Application Serial No. 09/452,976 filed December 2, 1999; Application Serial No. 09/327,756 filed June 7, 1999, which is a Continuation-in-Part of Application Serial No. 09/305,896 filed May 5, 1999, which is a Continuation-in-Part of copending Application No. 09/275,518 filed March 24, 1999, which is a Continuation-in-Part of copending Application Nos.: 09/274,265 filed March 22, 1999; 09/243,078 filed February 2, 1999; 09/241,930 filed February 2, 1999; 09/157,778 filed

September 21, 1998; 09/047,146 filed March 24, 1998, 08/949,915 filed October 14, 1997, now U.S. Letters Patent 6,158,659; 08/854,832 filed May 12, 1997, now U.S. Letters Patent 6,085,978; 08/886,806 filed April 22, 1997, now U.S. Letters Patent 5,984,185; 08/726,522 filed October 7, 1996, now U.S. Letters Patent 6,073,846; 08/573,949 filed December 18, 1995, now abandoned; each said application being commonly owned by Assignee, Metrologic Instruments, Inc., of Blackwood, New Jersey, and incorporated herein by reference as if fully set forth herein.

BACKGROUND OF THE INVENTION

Field of Invention

The present invention relates generally to an improved method of and system for illuminating moving as well as stationary objects, such as parcels, during image formation and detection operations, and also to an improved method of and system for acquiring and analyzing information about the physical attributes of such objects using such improved methods of object illumination, and digital image analysis.

Brief Description Of The State Of Knowledge In The Art

The use of image-based bar code symbol readers and scanners is well known in the field of auto-identification. Examples of image-based bar code symbol reading/scanning systems include, for example, hand-hand scanners, point-of-sale (POS) scanners, and industrial-type conveyor scanning systems.

Presently, most commercial image-based bar code symbol readers are constructed using charge-coupled device (CCD) image sensing/detecting technology. Unlike laser-based scanning technology, CCD imaging technology has particular illumination requirements which differ from application to application.

Most prior art CCD-based image scanners, employed in conveyor-type package identification systems, require high-pressure sodium, metal halide or halogen lamps and large, heavy and expensive parabolic or elliptical reflectors to produce sufficient light intensities to illuminate the large depth of field scanning fields supported by such industrial scanning systems. Even when the light from such lamps is collimated or focused using such reflectors, light strikes the target object other than where the imaging optics of the CCD-based camera are viewing. Since only a small fraction of the lamps output power is used to illuminate the CCD camera's field of view, the total output power of the lamps must be very high to obtain the illumination levels required along the field of view of the CCD camera. The balance of the output illumination power is simply wasted in the form of heat.

Most prior art CCD-based hand-held image scanners use an array of light emitting diodes (LEDs) to flood the field of view of the imaging optics in such scanning systems. A large percentage of the output illumination from these LED sources is dispersed to regions other than the field of view of the scanning system. Consequently, only a small percentage of the illumination is actually collected by the imaging optics of the system, Examples of prior art CCD hand-held image scanners employing LED illumination arrangements are disclosed in US Patent Nos. Re. 36,528, 5,777,314, 5,756,981, 5,627,358, 5,484,994, 5,786,582, and 6,123,261 to Roustaei, each assigned to Symbol Technologies, Inc. and incorporated herein by reference in its entirety. In such prior art CCD-based hand-held image scanners, an array of LEDs are mounted in a scanning head in front of a CCD-based image sensor that is provided with a cylindrical lens assembly. The LEDs are arranged at an angular orientation relative to a central axis passing through the scanning head so that a fan of light is emitted through the light transmission aperture thereof that expands with increasing distance away from the LEDs. The intended purpose of this LED illumination arrangement is to increase the "angular distance" and "depth of field" of CCD-based bar code symbol readers. However, even with such improvements in LED illumination techniques, the working distance of such hand-held CCD scanners can only be extended by using more LEDs within the scanning head of such scanners to produce greater illumination output therefrom, thereby increasing the cost, size and weight of such scanning devices.

Similarly, prior art "hold-under" and "hands-free presentation" type CCD-based image scanners suffer from shortcomings and drawbacks similar to those associated with prior art CCD-based hand-held image scanners.

Recently, there have been some technological advances made involving the use of laser illumination techniques in CCD-based image capture systems to avoid the shortcomings and drawbacks associated with using sodium-vapor illumination equipment, discussed above. In particular, US Patent No. 5,988,506 (assigned to Galore Scantec Ltd.), incorporated herein by reference, discloses the use of a cylindrical lens to generate from a single visible laser diode (VLD) a narrow focused line of laser light which fans out an angle sufficient to fully illuminate a code pattern at a working distance. As disclosed, mirrors can be used to fold the laser illumination beam towards the code pattern to be illuminated in the working range of the system. Also, a horizontal linear lens array consisting of lenses is mounted before a linear CCD image array, to receive diffused reflected laser light from the code symbol surface. Each single lens in the linear lens array forms its own image of the code line illuminated by the laser illumination beam. Also, subaperture diaphragms are required in the CCD array plane to (i) differentiate image fields, (ii) prevent diffused reflected laser light from passing through a lens and striking the image fields of neighboring lenses, and (iii) generate partially-overlapping fields of view from each of the neighboring elements in the lens array. However, while avoiding the use of external sodium vapor illumination equipment, this prior art laser-illuminated CCD-based image capture system suffers from several significant shortcomings and drawbacks. In particular, it requires very complex image forming optics which makes this system design difficult and expensive to manufacture, and imposes a number of undesirable constraints which are very

difficult to satisfy when constructing an auto-focus/auto-zoom image acquisition and analysis system for use in demanding applications.

When detecting images of target objects illuminated by a coherent illumination source (e.g. a VLD), “speckle”(i.e. substrate or paper) noise is typically modulated onto the PLIB during reflection/scattering, and ultimately speckle-noise patterns are produced at the CCD image detection array, severely reducing the signal-to-noise (SNR) ratio of the CCD camera system. In general, speckle-noise patterns are generated whenever the phase of the optical field is randomly modulated. The prior art system disclosed in US Patent No. 5,988,506 fails to provide any way of, or means for reducing speckle-noise patterns produced at its CCD image detector thereof, by its coherent laser illumination source.

The problem of speckle-noise patterns in laser scanning systems is mathamatically analyzed in the twenty-five (25) slide show entitled “Speckle Noise and Laser Scanning Systems” by Sasa Kresic-Juric, Emanuel Marom and Leonard Bergstein, of Symbol Technologies, Holtsville, NY, published at http://www.ima.umn.edu/industrial/99-2000/kresic/sld001.htm, and incorporated herein by reference. Notably, Slide 11/25 of this WWW publication summaries two generally well known methods of reducing speckle-noise by superimposing statistically independent (time-varying) speckle-noise patterns: (1) using multiple laser beams to illuminate different regions of the speckle-noise scattering plane (i.e. object); or (2) using multiple laser beams with different wavelengths to illuminate the scattering plane. Also, the celebrated textbook by J.C. Dainty, et al, entitled “Laser Speckle and Related Phenomena” (Second edition), published by Springer-Verlag, 1994, incorporated herein by reference, describes a collection of techniques which have been developed by others over the years in effort to reduce speckle-noise patterns in diverse application environments.

However, the prior art generally fails to disclose, teach or suggest how such prior art speckle-reduction techniques might be successfully practiced in laser illuminated CCD-based camera systems.

Thus, there is a great need in the art for an improved method of and apparatus for illuminating the surface of objects during image formation and detection operations, and also an improved method of and apparatus for producing digital images using such improved methods object illumination, while avoiding the shortcomings and drawbacks of prior art illumination, imaging and scanning systems and related methodologies.

OBJECTS AND SUMMARY OF THE PRESENT INVENTION

Accordingly, a primary object of the present invention is to provide an improved method of and system for illuminating the surface of objects during image formation and detection operations and also improved methods of and systems for producing digital images using such improved methods object illumination, while avoiding the shortcomings and drawbacks of prior art systems and methodologies.

Another object of the present invention is to provide such an improved method of and system for illuminating the surface of objects using a linear array of laser light emitting devices configured together to produce a substantially planar beam of laser illumination which extends in substantially the same plane as the field of view of the linear array of electronic image detection cells of the system, along at least a portion of its optical path within its working distance,

Another object of the present invention is to provide such an improved method of and system for producing digital images of objects using a visible laser diode array for producing a planar laser illumination beam for illuminating the surfaces of such objects, and also an electronic image detection array for detecting laser light reflected off the illuminated objects during illumination and imaging operations.

Another object of the present invention is to provide an improved method of and system for illuminating the surfaces of object to be imaged, using an array of planar laser illumination arrays which employ VLDs that are smaller, and cheaper, run cooler, draw less power, have longer lifetimes, and require simpler optics (i.e. because the spectral bandwidths of VLDs are very small compared to the visible portion of the electromagnetic spectrum).

Another object of the present invention is to provide such an improved method of and system for illuminating the surfaces of objects to be imaged, wherein the VLD concentrates all of its output power into a thin laser beam illumination plane which spatially coincides exactly with the field of view of the imaging optics of the system, so very little light energy is wasted.

Another object of the present invention is to provide a planar laser illumination and imaging (PLIIM) system, wherein the working distance of the system can be easily extended by simply changing the beam focusing and imaging optics, and without increasing the output power of the visible laser diode (VLD) sources employed therein.

Another object of the present invention is to provide a planar laser illumination and imaging system, wherein each planar laser illumination beam is focused so that the minimum width thereof (e.g. 0.6 mm along its non-spreading direction) occurs at a point or plane which is the farthest object distance at which the system is designed to capture images.

Another object of the present invention is to provide a planar laser illumination and imaging system, wherein a fixed focal length imaging subsystem is employed, and the laser beam focusing technique of the present invention helps compensate for decreases in the power density of the incident planar illumination beam due to the fact that the width of the planar laser illumination beam increases for increasing distances away from the imaging subsystem.

Another object of the present invention is to provide a planar laser illumination and imaging system, wherein a variable focal length (i.e. zoom) imaging subsystem is employed, and the laser beam focusing technique of the present invention helps compensate for (i) decreases in the power density of the incident illumination beam due to the fact that the width of the planar laser illumination beam (i.e. beamwidth) along the direction of the beam's planar extent increases for increasing distances away from the imaging subsystem, and (ii) any $1/r^2$ type losses that would typically occur when using the planar laser illumination beam of the present invention.

Another object of the present invention is to provide a planar laser illumination and imaging system, wherein scanned objects need only be illuminated along a single plane which is coplanar with a planar section of the field of view of the image formation and detection module being used in the PLIIM system.

Another object of the present invention is to provide a planar laser illumination and imaging system, wherein low-power, light-weight, high-response, ultra-compact, high-efficiency solid-state illumination producing devices, such as visible laser diodes (VLDs), are used to selectively illuminate ultra-narrow sections of a target object during image formation and detection operations, in contrast with high-power, low-response, heavy-weight, bulky, low-efficiency lighting equipment (e.g. sodium vapor lights) required by prior art illumination and image detection systems.

Another object of the present invention is to provide a planar laser illumination and imaging system, wherein the planar laser illumination technique enables modulation of the spatial and/or temporal intensity of the transmitted planar laser illumination beam, and use of simple (i.e. substantially monochromatic) lens designs for substantially monochromatic optical illumination and image formation and detection operations.

Another object of the present invention is to provide a planar laser illumination and imaging system, wherein special measures are undertaken to ensure that (i) a minimum safe distance is maintained between the VLDs in each PLIM and the user's eyes using a light shield, and (ii) the planar laser illumination beam is prevented from directly scattering into the FOV of the image formation and detection module within the system housing.

Another object of the present invention is to provide a planar laser illumination and imaging system, wherein the planar laser illumination beam and the field of view of the image formation and detection module do not overlap on any optical surface within the PLIIM system.

Another object of the present invention is to provide a planar laser illumination and imaging system, wherein the planar laser illumination beams are permitted to spatially overlap with the FOV of the imaging lens of the PLIIM only outside of the system housing, measured at a particular point beyond the light transmission window, through which the FOV is projected.

Another object of the present invention is to provide a planar laser illumination (PLIM) system for use in illuminating objects being imaged.

Another object of the present invention is to provide a planar laser illumination and imaging system, wherein the monochromatic imaging module is realized as an array of electronic image detection cells (e.g. CCD).

Another object of the present invention is to provide a planar laser illumination and imaging system, wherein the planar laser illumination arrays (PLIAs) and the image formation and detection (IFD) module (i.e. camera module) are mounted in strict optical alignment on an optical bench such that there is substantially no relative motion, caused by vibration or temperature changes, is permitted between the imaging lens within the IFD module and the VLD/cylindrical lens assemblies within the PLIAs.

Another object of the present invention is to provide a planar laser illumination and imaging system, wherein the imaging module is realized as a photographic image recording module.

Another object of the present invention is to provide a planar laser illumination and imaging system, wherein the imaging module is realized as an array of electronic image detection cells (e.g. CCD) having short integration time settings for high-speed image capture operations.

Another object of the present invention is to provide a planar laser illumination and imaging system, wherein a pair of planar laser illumination arrays are mounted about an image formation and detection module having a field of view, so as to produce a substantially planar laser illumination beam which is coplanar with the field of view during object illumination and imaging operations.

Another object of the present invention is to provide a planar laser illumination and imaging system, wherein an image formation and detection module projects a field of view through a first light transmission aperture formed in the system housing, and a pair of planar laser illumination arrays project a pair of planar laser illumination beams through second set of light transmission apertures which are optically isolated from the first light transmission aperture to prevent laser beam scattering within the housing of the system.

Another object of the present invention is to provide a planar laser illumination and imaging system, the principle of Gaussian summation of light intensity distributions is employed to produce a planar laser illumination beam having a power density across the width the beam which is substantially the same for both far and near fields of the system.

Another object of the present invention is to provide an improved method of and system for producing digital images of objects using planar laser illumination beams and electronic image detection arrays.

Another object of the present invention is to provide an improved method of and system for producing a planar laser illumination beam to illuminate the surface of objects and electronically detecting light reflected off the illuminated objects during planar laser beam illumination operations.

Another object of the present invention is to provide a hand-held laser illuminated image detection and processing device for use in reading bar code symbols and other character strings.

Another object of the present invention is to provide an improved method of and system for producing images of objects by focusing a planar laser illumination beam within the field of view of an imaging lens so that the minimum width thereof along its non-spreading direction occurs at the farthest object distance of the imaging lens.

Another object of the present invention is to provide planar laser illumination modules (PLIMs) for use in electronic imaging systems, and methods of designing and manufacturing the same.

Another object of the present invention is to provide planar laser illumination arrays (PLIAs) for use in electronic imaging systems, and methods of designing and manufacturing the same.

Another object of the present invention is to provide a unitary object attribute (i.e. feature) acquisition and analysis system completely contained within in a single housing of compact lightweight construction (e.g. less than 40 pounds).

Another object of the present invention is to provide such a unitary object attribute acquisition and analysis system, which is capable of (1) acquiring and analyzing in real-time the physical attributes of objects such as, for example, (i) the surface reflectivity characteristics of objects, (ii) geometrical characteristics of objects, including shape measurement, (iii) the motion (i.e. trajectory) and velocity of objects, as well as (iv) bar code symbol, textual, and other information-bearing structures disposed thereon, and (2) generating information structures representative thereof for use in diverse applications including, for example, object identification, tracking, and/or transportation/routing operations.

Another object of the present invention is to provide such a unitary object attribute acquisition and analysis system, wherein a multi-wavelength (i.e. color-sensitive) Laser Doppler Imaging and Profiling (LDIP) subsystem is provided for acquiring and analyzing (in real-time) the physical attributes of objects such as, for example, (i) the surface reflectivity characteristics of objects, (ii) geometrical characteristics of objects, including shape measurement, and (iii) the motion (i.e. trajectory) and velocity of objects.

Another object of the present invention is to provide such a unitary object attribute acquisition and analysis system, wherein an image formation and detection (i.e. camera) subsystem is provided having (i) a planar laser illumination and imaging (PLIIM) subsystem, (ii) intelligent auto-focus/auto-zoom imaging optics, and (iii) a high-speed electronic image detection array with height/velocity-driven photo-integration time control to ensure the capture of images having constant image resolution (i.e. constant dpi) independent of package height.

Another object of the present invention is to provide such a unitary object attribute acquisition and analysis system, wherein an advanced image-based bar code symbol decoder is provided for reading 1-D and 2-D bar code symbol labels on objects, and an advanced optical character recognition (OCR) processor is provided for reading textual information, such as alphanumeric character strings, representative within digital images that have been captured and lifted from the system.

Another object of the present invention is to provide such a unitary object attribute acquisition and analysis system for use in the high-speed parcel, postal and material handling industries.

Another object of the present invention is to provide such a unitary object attribute acquisition and analysis system, which is capable of being used to identify, track and route packages, as well as identify individuals for security and personnel control applications.

Another object of the present invention is to provide such a unitary object attribute acquisition and analysis system which enables bar code symbol reading of linear and two-

dimensional bar codes, OCR-compatible image lifting, dimensioning, singulation, object (e.g. package) position and velocity measurement, and label-to-parcel tracking from a single overhead-mounted housing measuring less than or equal to 20 inches in width, 20 inches in length, and 8 inches in height.

Another object of the present invention is to provide such a unitary object attribute acquisition and analysis system which employs a built-in source for producing a planar laser illumination beam that is coplanar with the field of view (FOV) of the imaging optics used to form images on an electronic image detection array, thereby eliminating the need for large, complex, high-power power consuming sodium vapor lighting equipment used in conjunction with most industrial CCD cameras.

Another object of the present invention is to provide such a unitary object attribute acquisition and analysis system, wherein the all-in-one (i.e. unitary) construction simplifies installation, connectivity, and reliability for customers as it utilizes a single input cable for supplying input (AC) power and a single output cable for outputting digital data to host systems.

Another object of the present invention is to provide such a unitary object attribute acquisition and analysis system, wherein such systems can be configured to construct multi-sided tunnel-type imaging systems, used in airline baggage-handling systems, as well as in postal and parcel identification, dimensioning and sortation systems.

Another object of the present invention is to provide such a unitary object attribute acquisition and analysis system, for use in (i) automatic checkout solutions installed within retail shopping environments (e.g. supermarkets), (ii) security and people analysis applications, (iii) object and/or material identification and inspection systems, as well as (iv) diverse portable, in-counter and fixed applications in virtual any industry.

Another object of the present invention is to provide such a unitary object attribute acquisition and analysis system in the form of a high-speed package dimensioning and identification system, wherein the PLIIM subsystem projects a field of view through a first light transmission aperture formed in the system housing, and a pair of planar laser illumination beams through second and third light transmission apertures which are optically isolated from the first light transmission aperture to prevent laser beam scattering within the housing of the system, and the LDIP subsystem projects a pair of laser beams at different angles through a fourth light transmission aperture.

Another object of the present invention is to provide a fully automated unitary-type package identification and measuring system contained within a single housing or enclosure, wherein a PLIIM-based scanning subsystem is used to read bar codes on packages passing below or near the system, while a package dimensioning subsystem is used to capture information about attributes (i.e. features) about the package prior to being identified.

Another object of the present invention is to provide such an automated package identification and measuring system, wherein LAser Detecting And Ranging (LADAR) based scanning methods are used to capture two-dimensional range data maps of the space above a

conveyor belt structure, and two-dimensional image contour tracing techniques and corner point reduction techniques are used to extract package dimension data therefrom.

Another object of the present invention is to provide such a unitary system, wherein the package velocity is automatically computed using package range data collected by a pair of amplitude-modulated (AM) laser beams projected at different angular projections over the conveyor belt.

Another object of the present invention is to provide such a system in which the lasers beams having multiple wavelengths are used to sense packages having a wide range of reflectivity characteristics.

Another object of the present invention is to provide an improved image-based hand-held scanners, body-wearable scanners, presentation-type scanners, and hold-under scanners which embody the PLIIM subsystem of the present invention.

Another object of the present invention is to provide a planar laser illumination and imaging (PLIIM) system which employs high-resolution wavefront control methods and devices to reduce the power of speckle-noise patterns within digital images acquired by the system.

Another object of the present invention is to provide such a PLIIM-based system, in which electrically/optically controlled liquid crystal (LC) spatial phase modulators are employed.

Another object of the present invention is to provide such a PLIIM-based system, in which planar laser illumination beams (PLIBs) rich in spectral-harmonic components on the time-frequency domain are optically generated using principles based on wavefront spatio-temporal dynamics.

Another object of the present invention is to provide such a PLIIM-based system, in which planar laser illumination beams (PLIBs) rich in spectral-harmonic components on the time-frequency domain are optically generated using principles based on wavefront non-linear dynamics.

Another object of the present invention is to provide such a PLIIM-based system, in which planar laser illumination beams (PLIBs) rich in spectral-harmonic components on the spatial-frequency domain are optically generated using principles based on wavefront spatio-temporal dynamics.

Another object of the present invention is to provide such a PLIIM-based system, in which planar laser illumination beams (PLIBs) rich in spectral-harmonic components on the spatial-frequency domain are optically generated using principles based on wavefront non-linear dynamics.

Another object of the present invention is to provide such a PLIIM-based system, in which planar laser illumination beams (PLIBs) rich in spectral-harmonic components are optically generated using diverse electro-optical devices including, for example, micro-electro-mehanical devices (MEMs) (e.g. deformable micro-mirrors), optically-addressed liquid crystal (LC) light valves, liquid crystal (LC) phase modulators, micro-oscillating reflectors (e.g. mirrors or spectrally-tuned polarizing reflective CLC film material), micro-oscillating refractive-type phase

modulators, micro-oscillating diffractive-type micro-oscillators, as well as rotating phase modulation discs, bands, rings and the like.

Another object of the present invention is to provide a novel planar laser illumination and imaging (PLIIM) system and method which employs a planar laser illumination array (PLIA) and electronic image detection array which cooperate to effectively reduce the speckle-noise pattern observed at the image detection array of the PLIIM system by reducing or destroying either (i) the spatial and/or temporal coherence of the planar laser illumination beams (PLIBs) produced by the PLIAs within the PLIIM system, or (ii) the spatial and/or temporal coherence of the planar laser illumination beams (PLIBs) that are reflected/scattered off the target and received by the image formation and detection (IFD) subsystem within the PLIIM system.

Another object of the present invention is to provide a novel method of and apparatus for reducing the power of speckle-noise patterns observable at the electronic image detection array of a PLIIM-based system, wherein the method involves modulating the spatial phase of the composite-type "transmitted" planar laser illumination beam (PLIB) prior to illuminating an object (e.g. package) therewith so that the object is illuminated with a spatially coherent-reduced laser beam and, as a result, numerous time-varying (random) speckle-noise patterns are produced and detected over the photo-integration time period of the image detection array in the IFD subsystem, thereby allowing these speckle-noise patterns to be temporally averaged and/or spatially averaged and the observable speckle-noise pattern reduced.

Another object of the present invention is to provide such a method of and apparatus for reducing the power of speckle-noise patterns observable at the electronic image detection array of a PLIIM-based system, wherein (i) the spatial phase of the transmitted PLIB is modulated along the planar extent thereof according to a spatial phase modulation function (SPMF) so as to modulate the phase along the wavefront of the PLIB and produce numerous substantially different time-varying speckle-noise patterns to occur at the image detection array of the IFD Subsystem during the photo-integration time period of the image detection array thereof, and also (ii) the numerous time-varying speckle-noise patterns produced at the image detection array are temporally and/or spatially averaged during the photo-integration time period thereof, thereby reducing the speckle-noise patterns observed at the image detection array.

Another object of the present invention is to provide such a method of and apparatus for reducing the power of speckle-noise patterns observable at the electronic image detection array of a PLIIM-based system, wherein the spatial phase modulation techniques that can be used to carry out the method include, for example: mechanisms for moving the relative position/motion of a cylindrical lens array and laser diode array, including reciprocating a pair of rectilinear cylindrical lens arrays relative to each other, as well as rotating a cylindrical lens array ring structure about each PLIM employed in the PLIIM-based system; rotating phase modulation discs having multiple sectors with different refractive indices to effect different degrees of phase delay along the wavefront of the PLIB transmitted (along different optical paths) towards the object to be illuminated; acousto-optical Bragg-type cells for enabling beam steering using

ultrasonic waves; ultrasonically-driven deformable mirror structures; a LCD-type spatial phase modulation panel; and other spatial phase modulation devices.

Another object of the present invention is to provide a novel method of and apparatus for reducing the power of speckle-noise patterns observable at the electronic image detection array of a PLIIM-based system, based on temporal intensity modulating the transmitted PLIB prior to illuminating an object therewith so that the object is illuminated with a temporally coherent-reduced laser beam and, as a result, numerous time-varying (random) speckle-noise patterns are produced at the image detection array in the IFD subsystem over the photo-integration time period thereof, and the numerous time-varying speckle-noise patterns are temporally and/or spatially averaged during the photo-integration time period, thereby reducing the RMS power of speckle-noise pattern observed at the image detection array.

Another object of the present invention is to provide such a method of and apparatus for reducing the the power of speckle-noise patterns observable at the electronic image detection array of a PLIIM-based system, wherein (i) the transmitted PLIB is temporal-intensity modulated according to a temporal intensity modulation (e.g. windowing) function (TIMF) causing the phase along the wavefront of the transmitted PLIB to be modulatd and numerous substantially different time-varying speckle-noise patterns produced at image detection array of the IFD Subsystem, and (ii) the numerous time-varying speckle-noise patterns produced at the image detection array are temporally and/or spatially averaged during the photo-integration time period thereof, thereby reducing the RMS power of RMS speckle-noise patterns observed (i.e. detected) at the image detection array.

Another object of the present invention is to provide such a method of and apparatus for reducing the power of speckle-noise patterns observable at the electronic image detection array of a PLIIM-based system, wherein temporal intensity modulation techniques which can be used to carry out the method include, for example: visible mode-locked laser diodes (MLLDs) employed in the planar laser illumination array; electro-optical temporal intensity modulation panels (i.e. shutters) disposed along the optical path of the transmitted PLIB; laser beam frequency-hoping devices; internala and external type laser beam frequency modulation (FM) devices; internal and external type laser beam amplitude modulation (AM) devices; and other temporal intensity modulation devices.

Another object of the present invention is to provide such a method of and apparatus for reducing the power of speckle-noise patterns observable at the electronic image detection array of a PLIIM-based system, wherein the spatial intensity modulation techniques that can be used to carry out the method include, for example: mechanisms for moving the relative position/motion of a spatial intensity modulation array (e.g. screen) relative to a cylindrical lens array and/or a laser diode array, including reciprocating a pair of rectilinear spatial intensity modulation arrays relative to each other, as well as rotating a spatial intensity modulation array ring structure about each PLIM employed in the PLIIM-based system; a rotating spatial intensity modulation disc; and other spatial intensity modulation devices.

Another object of the present invention is to provide a novel method of and apparatus for reducing the power of speckle-noise patterns observable at the electronic image detection array of a PLIIM-based system, wherein the method is based on spatial intensity modulating the composite-type "return" PLIB produced by the composite PLIB illuminating and reflecting and scattering off an object so that the return PLIB detected by the image detection array (in the IFD subsystem) constitutes a spatially coherent-reduced laser beam and, as a result, numerous time-varying speckle-noise patterns are detected over the photo-integration time period of the image detection array (in the IFD subsystem), thereby allowing these time-varying speckle-noise patterns to be temporally and spatially-averaged and the RMS power of the observed speckle-noise patterns reduced.

Another object of the present invention is to provide such a method of and apparatus for reducing the power of speckle-noise patterns observable at the electronic image detection array of a PLIIM-based system, wherein (i) the return PLIB produced by the transmitted PLIB illuminating and reflecting/scattering off an object is spatial-intensity modulated (along the dimensions of the image detection elements) according to a spatial-intensity modulation function (SIMF) so as to modulate the phase along the wavefront of the composite return PLIB and produce numerous substantially different time-varying speckle-noise patterns at the image detection array in the IFD Subsystem, and also (ii) temporally and spatially average the numerous time-varying speckle-noise patterns produced at the image detection array during the photo-integration time period thereof, thereby reducing the RMS power of the speckle-noise patterns observed at the image detection array.

Another object of the present invention is to provide such a method of and apparatus for reducing the power of speckle-noise patterns observable at the electronic image detection array of a PLIIM-based system, wherein spatial light modulation techniques which can be used to carry out the method include, for example: a mechanism for physically or photo-electronically rotating a spatial intensity modulator (e.g. apertures, irises, Fourier Transform plates, etc.) about the optical axis of the imaging lens of the camera module; and any other axially symmetric, rotating spatial intensity modulation element arranged before the entrance pupil of the camera module, through which the received PLIB beam may enter at any angle or orientation during illumination and image detection operations.

Another object of the present invention is to provide a novel method of and apparatus for reducing the power of speckle-noise patterns observable at the electronic image detection array of a PLIIM-based system, wherein the method is based on temporal intensity modulating the composite-type return PLIB produced by the composite PLIB illuminating and reflecting and scattering off an object so that the return composite PLIB detected by the image detection array in the IFD subsystem constitutes a temporally coherent-reduced laser beam and, as a result, numerous time-varying (random) speckle-noise patterns are detected over the photo-integration time period of the image detection array, thereby allowing these time-varying speckle-noise patterns to be temporally and spatially averaged and the RMS power of observed speckle-noise patterns reduced.

Another object of the present invention is to provide such a method of and apparatus for reducing the power of speckle-noise patterns observable at the electronic image detection array of a PLIIM-based system, wherein (i) the returned laser beam produced by the transmitted PLIB illuminating and reflecting/scattering off an object is temporal-intensity modulated according to a temporalintensity modulation (e.g. windowing) function (TIMF) so as to modulate the phase along the wavefront of the composite PLIB and produce numerous substantially different time-varying speckle-noise patterns at image detection array of the IFD Subsystem, and (ii) temporally and spatially averaging the numerous time-varying speckle-noise patterns at the image detection array during the photo-integration time period thereof, thereby reducing the RMS power of the speckle-noise patterns observed at the image detection array.

Another object of the present invention is to provide such a method of and apparatus for reducing the power of speckle-noise patterns observable at the electronic image detection array of a PLIIM-based system, wherein temporal intensity modulation techniques which can be used to carry out the method include, for example: high-speed electro-optical (e.g. ferro-electric, LCD, etc.) shutters located before the image detector along the optical axis of the camera subsystem; and any other temporal intensity modulation element arranged before the image detector along the optical axis of the camera subsystem, and through which the received PLIB beam may pass during illumination and image detection operations.

Another object of the present invention is to provide a novel planar laser illumination and imaging module which employs a planar laser illumination array (PLIA) comprising a plurality of visible laser diodes having a plurality of different characteristic wavelengths residing within different portions of the visible band.

Another object of the present invention is to provide such a novel PLIIM, wherein the visible laser diodes within the PLIA thereof are spatially arranged so that the spectral components of each neighboring visible laser diode (VLD) spatially overlap and each portion of the composite PLIB along its planar extent contains a spectrum of different characteristic wavelengths, thereby imparting multi-color illumination characteristics to the composite PLIB.

Another object of the present invention is to provide such a novel PLIIM, wherein the multi-color illumination characteristics of the composite PLIB reduce the temporal coherence of the laser illumination sources in the PLIA, thereby reducing the RMS power of the speckle-noise pattern observed at the image detection array of the PLIIM.

Another object of the present invention is to provide a novel planar laser illumination and imaging module (PLIIM) which employs a planar laser illumination array (PLIA) comprising a plurality of visible laser diodes (VLDs) which exhibit high "mode-hopping" spectral characteristics which cooperate on the time domain to reduce the temporal coherence of the laser illumination sources operating in the PLIA and produce numerous substantially different time-varying speckle-noise patterns during each photo-integration time period, thereby reducing the RMS power of the speckle-noise pattern observed at the image detection array in the PLIIM.

Another object of the present invention is to provide a novel planar laser illumination and imaging module (PLIIM) which employs a planar laser illumination array (PLIA) comprising a

plurality of visible laser diodes (VLDs) which are "thermally-driven" to exhibit high "mode-hopping" spectral characteristics which cooperate on the time domain to reduce the temporal coherence of the laser illumination sources operating in the PLIA, and thereby reduce the speckle noise pattern observed at the image detection array in the PLIIM accordance with the principles of the present invention.

Another object of the present invention is to provide a unitary (PLIIM-based) package dimensioning and identification system, wherein the various information signals are generated by the LDIP subsystem, and provided to a camera control computer, and wherein the camera control computer generates digital camera control signals which are provided to the image formation and detection (IFD subsystem (i.e. "camera") so that the system can carry out its diverse functions in an integrated manner, including (1) capturing digital images having (i) square pixels (i.e. 1:1 aspect ratio) independent of package height or velocity, (ii) significantly reduced speckle-noise levels, and (iii) constant image resolution measured in dots per inch (dpi) independent of package height or velocity and without the use of costly telecentric optics employed by prior art systems, (2) automatic cropping of captured images so that only regions of interest reflecting the package or package label require image processing by the image processing computer, and (3) automatic image lifting operations.

Another object of the present invention is to provide a novel bioptical-type planar laser illumination and imaging (PLIIM) system for the purpose of identifying products in supermarkets and other retail shopping environments (e.g. by reading bar code symbols thereon), as well as recognizing the shape, texture and color of produce (e.g. fruit, vegetables, etc.) using a composite multi-spectral planar laser illumination beam containing a spectrum of different characteristic wavelengths, to impart multi-color illumination characteristics thereto.

Another object of the present invention is to provide such a bioptical-type PLIIM-based system, wherein a planar laser illumination array (PLIA) comprising a plurality of visible laser diodes (VLDs) which intrinsically exhibit high "mode-hopping" spectral characteristics which cooperate on the time domain to reduce the temporal coherence of the laser illumination sources operating in the PLIA, and thereby reduce the speckle-noise pattern observed at the image detection array of the PLIIM-based system.

Another object of the present invention is to provide a bioptical PLIIM-based product dimensioning, analysis and identification system comprising a pair of PLIIM-based package identification and dimensioning subsystems, wherein each PLIIM-based subsystem produces multi-spectral planar laser illumination, employs a 1-D CCD image detection array, and is programmed to analyze images of objects (e.g. produce) captured thereby and determine the shape/geometry, dimensions and color of such products in diverse retail shopping environments; and

Another object of the present invention is to provide a bioptical PLIM-based product dimensioning, analysis and identification system comprising a pair of PLIM-based package identification and dimensioning subsystems, wherein each subsystem employs a 2-D CCD image detection array and is programmed to analyze images of objects (e.g. produce) captured thereby

and determine the shape/geometry, dimensions and color of such products in diverse retail shopping environments.

Another object of the present invention is to provide a unitary package identification and dimensioning system comprising: a LADAR-based package imaging, detecting and dimensioning subsystem capable of collecting range data from objects on the conveyor belt using a pair of multi-wavelength (i.e. containing visible and IR spectral components) laser scanning beams projected at different angular spacings; a PLIIM-based bar code symbol reading subsystem for producing a scanning volume above the conveyor belt, for scanning bar codes on packages transported therealong; an input/output subsystem for managing the inputs to and outputs from the unitary system; a data management computer, with a graphical user interface (GUI), for realizing a data element queuing, handling and processing subsystem, as well as other data and system management functions; and a network controller, operably connected to the I/O subsystem, for connecting the system to the local area network (LAN) associated with the tunnel-based system, as well as other packet-based data communication networks supporting various network protocols (e.g. Ethernet, Appletalk, etc).

Another object of the present invention is to provide a real-time camera control process carried out within a camera control computer in a PLIIM-based camera system, for intelligently enabling the camera system to zoom in and focus upon only the surfaces of a detected package which might bear package identifying and/or characterizing information that can be reliably captured and utilized by the system or network within which the camera subsystem is installed.

Another object of the present invention is to provide a real-time camera control process for significantly reducing the amount of image data captured by the system which does not contain relevant information, thus increasing the package identification performance of the camera subsystem, while using less computational resources, thereby allowing the camera subsystem to perform more efficiently and productivity.

Another object of the present invention is to provide a camera control computer for generating real-time camera control signals that drive the zoom and focus lens group translators within a high-speed auto-focus/auto-zoom digital camera subsystem so that the camera automatically captures digital images having (1) square pixels (i.e. 1:1 aspect ratio) independent of package height or velocity, (2) significantly reduced speckle-noise levels, and (3) constant image resolution measured in dots per inch (dpi) independent of package height or velocity.

Another object of the present invention is to provide an auto-focus/auto-zoom digital camera system employing a camera control computer which generates commands for cropping the corresponding slice (i.e. section) of the region of interest in the image being captured and buffered therewithin, or processed at an image processing computer.

Another object of the present invention is to provide a tunnel-type package identification and dimensioning (PIAD) system comprising a plurality of PLIIM-based package identification (PID) units arranged about a high-speed package conveyor belt structure, wherein the PID units are integrated within a high-speed data communications network having a suitable network topology and configuration.

Another object of the present invention is to provide such a tunnel-type PIAD system, wherein the top PID unit includes a LDIP subsystem, and functions as a master PID unit within the tunnel system, whereas the side and bottom PID units (which are not provided with a LDIP subsystem) function as slave PID units and are programmed to receive package dimension data (e.g. height, length and width coordinates) from the master PID unit, and automatically convert (i.e. transform) on a real-time basis these package dimension coordinates into their local coordinate reference frames for use in dynamically controlling the zoom and focus parameters of the camera subsystems employed in the tunnel-type system.

Another object of the present invention is to provide such a tunnel-type system, wherein the camera field of view (FOV) of the bottom PID unit is arranged to view packages through a small gap provided between sections of the conveyor belt structure.

Another object of the present invention is to provide a CCD camera-based tunnel system comprising auto-zoom/auto-focus CCD camera subsystems which utilize a "package-dimension data" driven camera control computer for automatic controlling the camera zoom and focus characteristics on a real-time manner.

Another object of the present invention is to provide such a CCD camera-based tunnel-type system, wherein the package-dimension data driven camera control computer involves (i) dimensioning packages in a global coordinate reference system, (ii) producing package coordinate data referenced to the global coordinate reference system, and (iii) distributing the package coordinate data to local coordinate references frames in the system for conversion of the package coordinate data to local coordinate reference frames, and subsequent use in automatic camera zoom and focus control operations carried out upon the dimensioned packages.

Another object of the present invention is to provide such a CCD camera-based tunnel-type system, wherein a LDIP subsystem within a master camera unit generates (i) package height, width, and length coordinate data and (ii) velocity data, referenced with respect to the global coordinate reference system R_{global}, and these package dimension data elements are transmitted to each slave camera unit on a data communication network, and once received, the camera control computer within the slave camera unit uses its preprogrammed homogeneous transformation to converts there values into package height, width, and length coordinates referenced to its local coordinate reference system.

Another object of the present invention is to provide such a CCD camera-based tunnel-type system, wherein a camera control computer in each slave camera unit uses the converted package dimension coordinates to generate real-time camera control signals which intelligently drive its camera's automatic zoom and focus imaging optics to enable the intelligent capture and processing of image data containing information relating to the identify and/or destination of the transported package.

Another object of the present invention is to provide a bioptical PLIIM-based product identification, dimensioning and analysis (PIDA) system comprising a pair of PLIIM-based package identification systems arranged within a compact POS housing having bottom and side light transmission apertures, located beneath a pair of imaging windows.

Another object of the present invention is to provide such a bioptical PLIIM-based system for capturing and analyzing color images of products and produce items, and thus enabling, in supermarket environments, "produce recognition" on the basis of color as well as dimensions and geometrical form.

Another object of the present invention is to provide such a bioptical system which comprises: a bottom PLIIM-based unit mounted within the bottom portion of the housing; a side PLIIM-based unit mounted within the side portion of the housing; an electronic product weigh scale mounted beneath the bottom PLIIM-based unit; and a local data communication network mounted within the housing, and establishing a high-speed data communication link between the bottom and side units and the electronic weigh scale.

Another object of the present invention is to provide such a bioptical PLIIM-based system, wherein each PLIIM-based subsystem employs (i) a plurality of visible laser diodes (VLDs) having different color producing wavelengths to produce a multi-spectral planar laser illumination beam (PLIB) from the side and bottom imaging windows, and also (ii) a 1-D (linear-type) CCD image detection array for capturing color images of objects (e.g. produce) as the objects are manually transported past the imaging windows of the bioptical system, along the direction of the indicator arrow, by the user or operator of the system (e.g. retail sales clerk).

Another object of the present invention is to provide such a bioptical PLIIM-based system, wherein the PLIIM-based subsystem installed within the bottom portion of the housing, projects an automatically swept PLIB and a stationary 3-D FOV through the bottom light transmission window.

Another object of the present invention is to provide such a bioptical PLIIM-based system, wherein each PLIIM-based subsystem comprises (i) a plurality of visible laser diodes (VLDs) having different color producing wavelengths to produce a multi-spectral planar laser illumination beam (PLIB) from the side and bottom imaging windows, and also (ii) a 2-D (area-type) CCD image detection array for capturing color images of objects (e.g. produce) as the objects are presented to the imaging windows of the bioptical system by the user or operator of the system (e.g. retail sales clerk).

Another object of the present invention is to provide a miniature planar laser illumination module (PLIM) on a semiconductor chip that can be fabricated by aligning and mounting a micro-sized cylindrical lens array upon a linear array of surface emit lasers (SELs) formed on a semiconductor substrate, encapsulated (i.e. encased) in a semiconductor package provided with electrical pins and a light transmission window, and emitting laser emission in the direction normal to the semiconductor substrate.

Another object of the present invention is to provide such a miniature planar laser illumination module (PLIM) on a semiconductor, wherein the laser output therefrom is a planar laser illumination beam (PLIB) composed of numerous (e.g. 100-400 or more) spatially incoherent laser beams emitted from the linear array of SELs.

Another object of the present invention is to provide such a miniature planar laser illumination module (PLIM) on a semiconductor, wherein each SEL in the laser diode array can

be designed to emit coherent radiation at a different characteristic wavelengths to produce an array of laser beams which are substantially temporally and spatially incoherent with respect to each other.

Another object of the present invention is to provide such a PLIM-based semiconductor chip, which produces a temporally and spatially coherent-reduced planar laser illumination beam (PLIB) capable of illuminating objects and producing digital images having substantially reduced speckle-noise patterns observable at the image detector of the PLIIM-based system in which the PLIM is employed.

Another object of the present invention is to provide a PLIM-based semiconductor which can be made to illuminate objects outside of the visible portion of the electromagnetic spectrum (e.g. over the UV and/or IR portion of the spectrum).

Another object of the present invention is to provide a PLIM-based semiconductor chip which embodies laser mode-locking principles so that the PLIB transmitted from the chip is temporal intensity-modulated at a sufficient high rate so as to produce ultra-short planes light ensuring substantial levels of speckle-noise pattern reduction during object illumination and imaging applications.

Another object of the present invention is to provide a PLIM-based semiconductor chip which contains a large number of VCSELs (i.e. real laser sources) fabricated on semiconductor chip so that speckle-noise pattern levels can be substantially reduced by an amount proportional to the square root of the number of independent laser sources (real or virtual) employed therein.

Another object of the present invention is to provide such a miniature planar laser illumination module (PLIM) on a semiconductor chip which does not require any mechanical parts or components to produce a spatially and/or temporally coherence reduced PLIB during system operation.

Another object of the present invention is to provide a novel planar laser illumination and imaging module (PLIIM) realized on a semiconductor chip. comprising a pair of micro-sized (diffractive or refractive) cylindrical lens arrays mounted upon a pair of large linear arrays of surface emitting lasers (SELs) fabricated on opposite sides of a linear CCD image detection array.

Another object of the present invention is to provide a PLIIM-based semiconductor chip, wherein both the linear CCD image detection array and linear SEL arrays are formed a common semiconductor substrate, and encased within an integrated circuit package having electrical connector pins, a first and second elongated light transmission windows disposed over the SEL arrays, and a third light transmission window disposed over the linear CCD image detection array.

Another object of the present invention is to provide such a PLIIM-based semiconductor chip, which can be mounted on a mechanically oscillating scanning element in order to sweep both the FOV and coplanar PLIB through a 3-D volume of space in which objects bearing bar code and other machine-readable indicia may pass.

Another object of the present invention is to provide a novel PLIIM-based semiconductor chip embodying a plurality of linear SEL arrays which are electronically-activated to electro-optically scan (i.e. illuminate) the entire 3-D FOV of the CCD image detection array without using mechanical scanning mechanisms.

Another object of the present invention is to provide such a PLIIM-based semiconductor chip, wherein the miniature 2D VLD/CCD camera can be realized by fabricating a 2-D array of SEL diodes about a centrally located 2-D area-type CCD image detection array, both on a semiconductor substrate and encapsulated within a IC package having a centrally-located light transmission window positioned over the CCD image detection array, and a peripheral light transmission window positioned over the surrounding 2-D array of SEL diodes.

Another object of the present invention is to provide such a PLIIM-based semiconductor chip, wherein light focusing lens element is aligned with and mounted over the centrally-located light transmission window to define a 3D field of view (FOV) for forming images on the 2-D image detection array, whereas a 2-D array of cylindrical lens elements is aligned with and mounted over the peripheral light transmission window to substantially planarize the laser emission from the linear SEL arrays (comprising the 2-D SEL array) during operation.

Another object of the present invention is to provide such a PLIIM-based semiconductor chip, wherein each cylindrical lens element is spatially aligned with a row (or column) in the 2-D CCD image detection array, and each linear array of SELs in the 2-D SEL array, over which a cylindrical lens element is mounted, is electrically addressable (i.e. activatable) by laser diode control and drive circuits which can be fabricated on the same semiconductor substrate.

Another object of the present invention is to provide such a PLIIM-based semiconductor chip which enables the illumination of an object residing within the 3D FOV during illumination operations, and the formation of an image strip on the corresponding rows (or columns) of detector elements in the CCD array.

As will be described in greater detail in the Detailed Description of the Illustrative Embodiments set forth below, such objectives are achieved in novel methods of and systems for illuminating objects (e.g. bar coded packages, textual materials, graphical indicia, etc.) using planar laser illumination beams (PLIBs) having substantially-planar spatial distribution characteristics that extend through the field of view (FOV) of image formation and detection modules (e.g. realized within a CCD-type digital electronic camera, or a 35 mm optical-film photographic camera) employed in such systems.

In each illustrative embodiment of the present invention, the substantially planar laser illumination beams are preferably produced from a planar laser illumination beam array (PLIA) comprising a plurality of planar laser illumination modules (PLIMs). Each PLIM comprises a visible laser diode (VLD), a focusing lens, and a cylindrical optical element arranged therewith. The individual planar laser illumination beam components produced from each PLIM are optically combined within the PLIA to produce a composite substantially planar laser illumination beam having substantially uniform power density characteristics over the entire spatial extend thereof and thus the working range of the system, in which the PLIA is embodied.

Preferably, each planar laser illumination beam component is focused so that the minimum beam width thereof occurs at a point or plane which is the farthest or maximum object distance at which the system is designed to acquire images. In the case of both fixed and variable focal length imaging systems, this inventive principle helps compensate for decreases in the power density of the incident planar laser illumination beam due to the fact that the width of the planar laser illumination beam increases in length for increasing object distances away from the imaging subsystem.

By virtue of the novel principles of the present invention, it is now possible to use both VLDs and high-speed CCD-type image detectors in conveyor, hand-held and hold-under type imaging applications alike, enjoying the advantages and benefits that each such technology has to offer, while avoiding the shortcomings and drawbacks hitherto associated therewith.

These and other objects of the present invention will become apparent hereinafter and in the Claims to Invention.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present invention, the following Detailed Description of the Illustrative Embodiment should be read in conjunction with the accompanying Drawings, wherein:

Fig. 1A is a schematic representation of a first generalized embodiment of the planar laser illumination and (electronic) imaging (PLIIM) system of the present invention, wherein a pair of planar laser illumination arrays (PLIAs) are mounted on opposite sides of a linear (i.e. 1-dimensional) type image formation and detection (IFD) or camera module having a fixed focal length imaging lens, a fixed focal distance and fixed field of view, such that the planar illumination array produces a stationary (i.e. non-scanned) plane of laser beam illumination which is disposed substantially coplanar with the field of view of the image formation and detection module during object illumination and image detection operations carried out by the PLIIM system on a moving bar code symbol or other graphical structure;

Fig. 1B1 is a schematic representation of the first illustrative embodiment of the PLIIM system of the present invention shown in Fig. 1A, wherein the field of view of the image formation and detection (IFD) module is folded in the downwardly imaging direction by the field of view folding mirror so that both the folded field of view and resulting stationary planar laser illumination beams produced by the planar illumination arrays are arranged in a substantially coplanar relationship during object illumination and image detection operations;

Fig. 1B2 is a schematic representation of the PLIIM system shown in Fig. 1A, wherein the linear image formation and detection module is shown comprising a linear array of photo-electronic detectors realized using CCD technology, each planar laser illumination array is shown comprising an array of planar laser illumination modules;

Fig. 1C is a schematic representation of a single planar laser illumination module (PLIM) used to construct each planar laser illumination array shown in Fig. 1B, wherein the planar laser

illumination beam emanates substantially within a single plane along the direction of beam propagation towards an object to be optically illuminated;

Fig. 1D is a schematic diagram of the planar laser illumination module of Fig. 1C, shown comprising a visible laser diode (VLD), a light collimating lens, and a cylindrical-type lens element configured together to produce a beam of planar laser illumination;

Fig. 1E1 is a plan view of the VLD, collimating lens and cylindrical lens assembly employed in the planar laser illumination module of Fig. 1C, showing that the focused laser beam from the collimating lens is directed on the input side of the cylindrical lens, and the output beam produced therefrom is a planar laser illumination beam expanded (i.e. spread out) along the plane of propagation;

Fig. 1E2 is an elevated side view of the VLD, collimating lens and cylindrical lens assembly employed in the planar laser illumination module of Fig. 1C, showing that the laser beam is transmitted through the cylindrical lens without expansion in the direction normal to the plane of propagation, but is focused by the collimating lens at a point residing within a plane located at the farthest object distance supported by the PLIIM system;

Fig. 1F is a block schematic diagram of the PLIIM system shown in Fig. 1A, comprising a pair of planar laser illumination arrays (driven by a set of VLD driver circuits that can drive the VLDs in a high-frequency pulsed-mode of operation), a linear-type image formation and detection (IFD) or camera module, a stationary field of view folding mirror, an image frame grabber, an image data buffer, an image processing computer, and a camera control computer;

Fig. 1G1 is a schematic representation of an exemplary re PLIIM system of Fig. 1A, shown comprising a linear image formation and detec pair of planar laser illumination arrays, and a field of view (FOV) folding mirror fixed field of view of the linear image formation and detection module in a direct anar with the plane of laser illumination beams produced by the planar laser illumin

Fig. 1G2 is a plan view schematic representation of the PLIIM 1G1, taken along line 1G2-1G2 therein, showing the spatial extent of the fixed f the linear image formation and detection module in the illustrative embodiment o vention;

Figs. 1G3 is an elevated end view schematic representation of t m of Fig. 1G1, taken along line 1G3-1G3 therein, showing the fixed field of v ar image formation and detection module being folded in the downwardly imagin the field of view folding mirror, the planar laser illumination beam produced ar laser illumination module being directed in the imaging direction such that b field of view and planar laser illumination beams are arranged in a substantially coplanar relationship during object illumination and image detection operations;

Fig. 1G4 is an elevated side view schematic representation of the PLIIM system of Fig. 1G1, taken along line 1G4-1G4 therein, showing the field of view of the image formation and detection module being folded in the downwardly imaging direction by the field of view folding mirror, and the planar laser illumination beam produced by each planar laser illumination module being directed along the imaging direction such that both the folded field of view and stationary

planar laser illumination beams are arranged in a substantially coplanar relationship during object illumination and image detection operations;

Fig. 1G5 is an elevated side view of the PLIIM system of Fig. 1G1, showing the spatial limits of the fixed field of view (FOV) of the image formation and detection module when set to image the tallest packages moving on a conveyor belt structure, as well as the spatial limits of the fixed FOV of the image formation and detection module when set to image objects having height values close to the surface height of the conveyor belt structure;

Fig. 1G6 is a perspective view of a first type of light shield which can be used in the PLIIM system of Fig. 1G1, to visually block portions of planar laser illumination beams which extend beyond the scanning field of the system, and could pose a health risk to humans if viewed thereby during system operation;

Fig. 1G7 is a perspective view of a second type of light shield which can be used in the PLIIM system of Fig. 1G1, to visually block portions of planar laser illumination beams which extend beyond the scanning field of the system, and could pose a health risk to humans if viewed thereby during system operation;

Fig. 1G8 is a perspective view of one planar laser illumination array (PLIA) employed in the PLIIM system of Fig. 1G1, showing an array of visible laser diodes (VLDs), each mounted within a VLD mounting block wherein a focusing lens is mounted and on the end of which there is a v-shaped notch or recess, within which a cylindrical lens element is mounted, and wherein each such VLD mounting block is mounted on an L-bracket for mounting within the housing of the PLIIM system;

Fig. 1G9 is an elevated end view of one planar laser illumination array (PLIA) employed in the PLIIM system of Fig. 1G1, taken along line 1G9-1G9 thereof;

Fig. 1G10 is an elevated side view of one planar laser illumination array (PLIA) employed in the PLIIM system of Fig. 1G1, taken along line 1G10-1G10 therein, showing a visible laser diode (VLD) and a focusing lens mounted within a VLD mounting block, and a cylindrical lens element mounted at the end of the VLD mounting block, so that the central axis of the cylindrical lens element is substantially perpendicular to the optical axis of the focusing lens;

Fig. 1G11 is an elevated side view of one of the VLD mounting blocks employed in the PLIIM system of Fig. 1G1, taken along a viewing direction which is orthogonal to the central axis of the cylindrical lens element mounted to the end portion of the VLD mounting block;

Fig. 1G12 is an elevated plan view of one of VLD mounting blocks employed in the PLIIM system of Fig. 1G1, taken along a viewing direction which is parallel to the central axis of the cylindrical lens element mounted to the VLD mounting block;

Fig. 1G13 is an elevated side view of the collimating lens element installed within each VLD mounting block employed in the PLIIM system of Fig. 1G1;

Fig. 1G14 is an axial view of the collimating lens element installed within each VLD mounting block employed in the PLIIM system of Fig. 1G1;

Fig. 1G15A is an elevated plan view of one of planar laser illumination modules (PLIMs) employed in the PLIIM system of Fig. 1G1, taken along a viewing direction which is parallel to the central axis of the cylindrical lens element mounted in the VLD mounting block thereof, showing that the cylindrical lens element expands (i.e. spreads out) the laser beam along the direction of beam propagation so that a substantially planar laser illumination beam is produced, which is characterized by a plane of propagation that is coplanar with the direction of beam propagation;

Fig. 1G15B is an elevated plan view of one of the PLIMs employed in the PLIIM system of Fig. 1G1, taken along a viewing direction which is perpendicular to the central axis of the cylindrical lens element mounted within the axial bore of the VLD mounting block thereof, showing that the focusing lens planar focuses the laser beam to its minimum beam width at a point which is the farthest distance at which the system is designed to capture images, while the cylindrical lens element does not expand or spread out the laser beam in the direction normal to the plane of propagation of the planar laser illumination beam;

Fig. 1H1 is a geometrical optics model for the imaging subsystem employed in the linear-type image formation and detection module in the PLIIM system of the first generalized embodiment shown in Fig. 1A;

Fig. 1H2 is a geometrical optics model for the imaging subsystem and linear image detection array employed in the linear-type image detection array of the image formation and detection module in the PLIIM system of the first generalized embodiment shown in Fig. 1A;

Fig. 1H3 is a graph, based on thin lens analysis, showing that the image distance at which light is focused through a thin lens is a function of the object distance at which the light originates;

Fig. 1H4 is a schematic representation of an imaging subsystem having a variable focal distance lens assembly, wherein a group of lens can be controllably moved along the optical axis of the subsystem, and having the effect of changing the image distance to compensate for a change in object distance, allowing the image detector to remain in place;

Fig. 1H5 is schematic representation of a variable focal length (zoom) imaging subsystem which is capable of changing its focal length over a given range, so that a longer focal length produces a smaller field of view at a given object distance;

Fig. 1H6 is a schematic representation illustrating (i) the projection of a CCD image detection element (i.e. pixel) onto the object plane of the image formation and detection (IFD) module (i.e. camera subsystem) employed in the PLIIM systems of the present invention, and (ii) various optical parameters used to model the camera subsystem;

Fig. 1I1 is a schematic representation of the PLIIM system of Fig. 1A embodying a *first* generalized method of reducing the RMS power of observable speckle-noise patterns, wherein the planar laser illumination beam (PLIB) produced from the PLIIM system is spatial phase modulated by a spatial phase modulation function (SIMF) prior to object illumination, so that the object (e.g. package) is illuminated with spatially coherent-reduced laser beam and, as a result, numerous substantially different time-varying speckle-noise patterns are produced and detected

over the photo-integration time period of the image detection array, thereby allowing the speckle-noise patterns to be temporally averaged over the photo-integration time period and/or spatially averaged over the image detection element and the observable speckle-noise pattern reduced at the image detection array;

Fig. 1I2A is a schematic representation of the PLIM system of Fig. 1I1, illustrating the first generalized speckle-noise pattern reduction method of the present invention applied to the planar laser illumination array (PLIA) employed therein, wherein (i) the transmitted PLIB is spatial phase modulated along the planar extent thereof according to a spatial phase modulation function (SIMF) so as to modulate the phase along the wavefront of the PLIB and produce numerous substantially different speckle-noise patterns at the image detection array of the IFD Subsystem during the photo-integration time period thereof, so that the numerous time-varying speckle-noise patterns produced at the image detection array can be temporally and/or spatially averaged during the photo-integration time period thereof, thereby reducing the speckle-noise patterns observed at the image detection array;

Fig. 1I2B is a high-level flow chart setting forth the primary steps involved in practicing the *first* generalized method of reducing observable speckle-noise patterns in PLIIM-based Systems, illustrated in Figs. 1I1 and 1I2A;

Fig. 1I3A is a perspective view of an optical assembly comprising a planar laser illumination array (PLIA) with a pair of refractive-type cylindrical lens arrays, and an electronically-controlled mechanism for micro-oscillating the cylindrical lens arrays using two pairs of ultrasonic transducers arranged in a push-pull configuration so that transmitted planar laser illumination beam (PLIB) is spatially phase modulated along the planar extent thereof causing the phase among the wavefront of the PLIB to be modulated and numerous (i.e. many) substantially different time-varying speckle-noise patterns produced at the image detection array of the IFD Subsystem during the photo-integration time period thereof, and the numerous time-varying speckle-noise patterns produced at the image detection array can be temporally and/or spatially averaged during the photo-integration time period thereof, thereby reducing the speckle-noise patterns observed at the image detection array;

Fig. 1I3B is a perspective view of the pair of refractive-type cylindrical lens arrays employed in the optical assembly shown in Fig. 1I3A;

Fig. 1I3C is a perspective view of the dual array support frame employed in the optical assembly shown in Fig. 1I3A;

Fig. 1I3D is a schematic representation of the dual refractive-type cylindrical lens array structure employed in Fig. 1I3A, shown configured between two pairs of ultrasonic transducers (or flexural elements driven by voice-coil type devices) operated in a push-pull mode of operation, so that at least one cylindrical lens array is constantly moving when the other array is momentarily stationary during lens array direction reversal;

Fig. 1I3E is a geometrical model of a subsection of the optical assembly shown in Fig. 1I3A, illustrating the first order parameters involved in the PLIB micro-oscillation (i.e. spatial

phase modulation) process which are required for at least one cycle of speckle-noise pattern variation occurs at the image detection array of the IFD module (i.e. camera subsystem);

Fig. 1I3F is a pictorial representation of a string of numbers imaged by the PLIIM system of the present invention without the use of the first generalized speckle-noise reduction techniques of the present invention;

Fig. 1I3G is a pictorial representation of the same string of numbers (shown in Fig. 1G13B1) imaged by the PLIIM system of the present invention using the first generalized speckle-noise reduction technique of the present invention, and showing a significant reduction in speckle-noise patterns observed in digital images captured by the electronic image detection array employed in the PLIIM system of the present invention provided with the apparatus of Fig. 1I3A;

Fig. 1I4A is a perspective view of an optical assembly comprising the a with a pair of (holographically-fabricated) diffractive-type cylindrical lens arrays, and an electronically-controlled mechanism for micro-oscillating a pair of cylindrical lens arrays using a pair of ultrasonic transducers arranged in a push-pull configuration so that the composite planar laser illumination beam is spatial phase modulated along the planar extent thereof, causing the phase along the wavefront of the PLIB to be modulated and numerous substantially different time-varying speckle-noise patterns produced at the image detection array of the IFD Subsystem during the photo-integration time period thereof, so that the numerous time-varying speckle-noise patterns produced at the image detection array can be temporally and spatially averaged during the photo-integration time period thereof, thereby reducing the speckle-noise patterns observed at the image detection array;

Fig. 1I4B is a perspective view of the refractive-type cylindrical lens arrays employed in the optical assembly shown in Fig. 1I4A;

Fig. 1I4C is a perspective view of the dual array support frame employed in the optical assembly shown in Fig. 1I4A;

Fig. 1I4D is a schematic representation of the dual refractive-type cylindrical lens array structure employed in Fig. 1I4A, shown configured between a pair of ultrasonic transducers (or flexural elements driven by voice-coil type devices) operated in a push-pull mode of operation;

Fig. 1I5A is a perspective view of an optical assembly comprising a PLIA with a stationary refractive-type cylindrical lens array, and an electronically-controlled mechanism for micro-oscillating a pair of reflective-elements pivotally connected to each other at a common pivot point, relative to a stationary reflective element (e.g mirror element) and the stationary refractive-type cylindrical lens array so that the transmitted PLIB is spatial phase modulated along the planar extent thereof, causing the phase along the wavefront of the transmitted PLIB to be modulated and numerous substantially different time-varying speckle-noise patterns produced at the image detection array of the IFD Subsystem during the photo-integration time period thereof, so that the the numerous time-varying speckle-noise patterns produced at the image detection array can be temporally and spatially averaged during the photo-integration time period thereof, thereby reducing the speckle-noise patterns observed at the image detection array;

Fig. 1I5B is a enlarged perspective view of the pair of micro-oscillating reflective elements employed in the optical assembly shown in Fig. 1I5A;

Fig. 1I5C is a schematic representation, taken along an elevated side view of the optical assembly shown in Fig. 1I5A, showing the optical path which the laser illumination beam produced thereby travels towards the target object to be illuminated;

Fig. 1I5D is a schematic representation of one micro-oscillating reflective element in the pair employed in Fig. 1I5D, shown configured between a pair of ultrasonic transducers operated in a push-pull mode of operation, so as to undergo micro-oscillation;

Fig. 1I6A is a perspective view of an optical assembly comprising a PLIA with refractive-type cylindrical lens array, and an electro-acoustically controlled PLIB micro-oscillation mechanism realized by an acousto-optical (i.e. Bragg Cell) beam deflection device, through which each laser beam within the PLIM is transmitted and deflected in response to acoustical signals propagating through the electro-acoustical device so that the transmitted PLIB is spatial phase modulated along the planar extent thereof, causing the phase along the wavefront of the transmitted PLIB to be modulated and numerous substantially different time-varying speckle-noise patterns produced at the image detection array of the IFD Subsystem during the photo-integration time period thereof, so that the numerous time-varying speckle-noise patterns produced at the image detection array can be temporally and spatially averaged during the photo-integration time period thereof, thereby reducing the speckle-noise patterns observed at the image detection array;

Fig. 1I6B is a schematic representation, taken along the cross-section of the optical assembly shown in Fig. 1I6A, showing the optical path which each laser beam within the PLIM travels on its way towards a target object to be illuminated;

Fig. 1I7A is a perspective view of an optical assembly comprising a PLIA with a stationary cylindrical lens array, and an electronically-controlled PLIB micro-oscillation mechanism realized by (i) a piezo-electrically driven deformable mirror (DM) structure arranged in front of the stationary cylindrical lens array (e.g. operating according to refractive, diffractive and/or reflective principles), and (ii) a stationary beam folding mirror, wherein the surface of the DM structure is periodically deformed at frequencies in the 100kHz range and at few microns amplitude causing the reflective surface thereof to exhibit moving ripples aligned along the direction that is perpendicular to planar extent of the PLIB (i.e. along laser beam spread) so that the transmitted PLIB is spatial phase modulated along the planar extent thereof, the phase along the wavefront of the transmitted PLIB is modulated, numerous substantially different time-varying speckle-noise patterns are produced at the image detection array of the IFD Subsystem during the photo-integration time period thereof, and the numerous time-varying speckle-noise patterns produced at the image detection array are temporally and spatially averaged during the photo-integration time period thereof, thereby reducing the speckle-noise patterns observed at the image detection array;

Fig. 1I7B is a enlarged perspective view of the stationary beam folding mirror structure employed in the optical assembly shown in Fig. 1I7A;

Fig. 1I7C is a schematic representation, taken along an elevated side view of the optical assembly shown in Fig. 1I7A, showing the optical path which the laser illumination beam produced thereby travels towards the target object to be illuminated while undergoing phase modulation by the piezo-electrically driven deformable mirror structure;

Fig. 1I8A is a perspective view of an optical assembly comprising a PLIA with a stationary refractive-type cylindrical lens array, and an electronically-controlled PLIB micro-oscillation mechanism realized by a refractive-type phase-modulation disc that is rotated about its axis through the composite planar laser illumination beam so as to spatial phase modulate the transmitted PLIB, causing the phase along the wavefront of the transmitted PLIB to be modulated and numerous substantially different time-varying speckle-noise patterns produced at the image detection array of the IFD Subsystem during the photo-integration time period of the image detection array thereof, so that the numerous time-varying speckle-noise patterns produced at the image detection array can be temporally and spatially averaged during the photo-integration time period thereof, thereby reducing the speckle-noise patterns observed at the image detection array;

Fig. 1I8B is an elevated side view of the refractive-type phase-modulation disc employed in the optical assembly shown in Fig. 1I8A;

Fig. 1I8C is a plan view of the optical assembly shown in Fig. 1I8A, showing the resulting micro-oscillation of the PLIB components caused by the phase modulation introduced by the refractive-type phase modulation disc rotating in the optical path of the PLIB;

Fig. 1I8D is a schematic representation of the refractive-type phase-modulation disc employed in the optical assembly shown in Fig. 1I8A, showing the numerous sections of the disc, which have refractive indices that vary sinusoidally at different angular positions along the disc;

Fig. 1I8E is a schematic representation of the rotating phase-modulation disc and stationary cylindrical lens array employed in the optical assembly shown in Fig. 1I8A, showing that the electric field components produced from neighboring elements in the array contribute to the resultant electric field intensity at each detector element in the image detection array of the IFD Subsystem;

Fig. 1I8F is a schematic representation of an optical assembly for reducing the RMS power of speckle-noise patterns in PLIIM-based systems, shown comprising a backlit transmissive-type phase-only LCD (PO-LCD) phase modulation panel and a cylindrical lens array positioned closely thereto;

Fig. 1I8G is a plan view of the optical assembly shown in Fig. 1I8F, showing the resulting micro-oscillation of the PLIB components caused by the phase modulation introduced by the phase-only type LCD-based phase modulation panel disposed along the optical path of the PLIB;

Fig. 1I9A is a perspective view of an optical assembly comprising a PLIA and an electronically-controlled phase-modulation mechanism realized by a refractive-type cylindrical lens array ring structure that is rotated about its axis through a transmitted PLIB so as to spatial

phase modulate the transmitted PLIB along the planar extended thereof, causing the phase along the wavefront of the transmitted PLIB to be modulated and numerous substantially different time-varying speckle-noise patterns produced at the image detection array of the IFD Subsystem during the photo-integration time period thereof, so that the numerous time-varying speckle-noise patterns produced at the image detection array can be temporally and spatially averaged during the photo-integration time period thereof, thereby reducing the speckle-noise patterns observed at the image detection array;

Fig. 1I9B is a plan view of the optical assembly shown in Fig. 1I9A, showing the resulting micro-oscillation of the PLIB components caused by the phase modulation introduced by the cylindrical lens ring structure rotating about each PLIA in the PLIIM-based system;

Fig. 1I10A is a perspective view of an optical assembly comprising a PLIA, and an electronically-controlled PLIB phase-modulation mechanism realized by a diffractive-type (e.g. holographic) cylindrical lens array ring structure that is rotated about its axis through the transmitted PLIB so as to spatial phase modulate the transmitted PLIB along the planar extent thereof, causing the phase along the wavefront of the transmitted PLIB to be modulated and numerous substantially different time-varying speckle-noise patterns produced at the image detection array of the IFD Subsystem during the photo-integration time period thereof, so that the numerous time-varying speckle-noise patterns produced at the image detection array can be temporally and spatially averaged during the photo-integration time period thereof, thereby reducing the speckle-noise patterns observed at the image detection array;

Fig. 1I10B is a plan view of the optical assembly shown in Fig. 1I10A, showing the resulting micro-oscillation of the PLIB components caused by the phase modulation introduced by the cylindrical lens ring structure rotating about each PLIA in the PLIIM-based system;

Fig. 1I11A is a perspective view of a PLIIM-based system as shown in Fig. 1I1 embodying a pair of optical assemblies, each comprising an electronically-controlled PLIB phase-modulation mechanism stationarily mounted between a pair of PLIAs towards which the PLIAs direct a PLIB, wherein the PLIB phase-modulation mechanism is realized by a reflective-type phase modulation disc structure having a cylindrical surface with random surface irregularities, rotated about its axis through the PLIB so as to spatial phase modulate the transmitted PLIB, causing the phase along the wavefront of the transmitted PLIB to be modulated and numerous substantially different time-varying speckle-noise patterns produced at the image detection array of the IFD Subsystem during the photo-integration time period thereof, so that the numerous time-varying speckle-noise patterns produced at the image detection array can be temporally and spatially averaged during the photo-integration time period thereof, thereby reducing the speckle-noise patterns observed at the image detection array;

Fig. 1I11B is an elevated side view of the PLIM-based system shown in Fig. 1I11A;

Fig. 1I11C is an elevated side view of one of the optical assemblies shown in Fig. 1I11A, schematically illustrating how the individual beam components in the PLIB are directed onto the rotating reflective-type phase modulation disc structure and are phase modulated as they are

reflected thereoff in a direction of coplanar alignment with the field of view (FOV) of the IFD subsystem of the PLIIM-based system;

FIG. 1I12 is a schematic of the PLIIM system of Fig. 1A embodying a *second* generalized method of reducing the RMS power of observable speckle-noise patterns, wherein the planar laser illumination beam (PLIB) produced from the PLIIM system is temporal intensity modulated by a temporal intensity modulation function (TIMF) prior to object illumination, so that the target object (e.g. package) is illuminated with a temporally coherent-reduced laser beam and, as a result, numerous substantially different time-varying speckle-noise patterns are produced and detected over the photo-integration time period of the image detection array, thereby allowing the speckle-noise patterns to be temporally averaged over the photo-integration time period and/or spatially averaged over the image detection element and the observable speckle-noise pattern reduced;

Fig. 1I13A is a schematic representation of the PLIIM-based system of Fig. 1I12, illustrating the second generalized speckle-noise pattern reduction method of the present invention applied to the planar laser illumination array (PLIA) employed therein, wherein (i) the transmitted PLIB is temporal intensity modulated along the planar extent thereof according to a temporal-intensity modulation function (TIMF) so as to modulate the phase along the wavefront of the PLIB and produce many substantially different time-varying speckle-noise patterns at the image detection array of the IFD Subsystem during the photo-integration time period thereof, and (ii) the numerous time-varying speckle-noise patterns produced at the image detection array are temporally and spatially averaged during the photo-integration time period thereof, thereby reducing the speckle-noise patterns observed at the image detection array;

Fig. 1I13B is a high-level flow chart setting forth the primary steps involved in practicing the *second* generalized method of reducing observable speckle-noise patterns in PLIIM-based systems, illustrated in Figs. 1I12 and 1I13A;

Fig. 1I14A is a perspective view of an optical assembly comprising a PLIA with a cylindrical lens array, and an electronically-controlled PLIB modulation mechanism realized by a high-speed laser beam temporal-intensity modulation structure (e.g. electro-optical gating switching device) arranged in front of the cylindrical lens array, wherein (i) the transmitted PLIB is temporal intensity modulated according to a temporal intensity modulation (e.g. windowing) function (TIMF) causing the phase along the wavefront of the transmitted PLIB to be modulated and numerous substantially different time-varying speckle-noise patterns produced at image detection array of the IFD Subsystem during the photo-integration time period thereof, and (ii) the numerous time-varying speckle-noise patterns produced at the image detection array are temporally and spatially averaged during the photo-integration time period thereof, thereby reducing the speckle-noise patterns observed at the image detection array;

Fig. 1I14B is a schematic representation, taken along the cross-section of the optical assembly shown in Fig. 1I14A, showing the optical path which each optically-gated PLIB component within the PLIB travels on its way towards the target object to be illuminated;

Fig. 1I15A is a perspective view of an optical assembly comprising a PLIA embodying a plurality of visible mode-locked laser diodes (MLLDs), arranged in front of a cylindrical lens array, wherein (i) the transmitted PLIB is temporal-intensity modulated according to a temporal-intensity modulation (e.g. windowing) function (TIMF) so as to modulate the phase along the wavefront of the transmitted PLIB and produce numerous substantially different speckle-noise pattern at the image detection array of the IFD subsystem during the photo-integration time period therof, so that the numerous time-varying speckle-noise patterns produced at the image detection array can be temporally and spatially averaged during the photo-integration time period thereof, thereby reducing the speckle-noise patterns observed at the image detection array;

Fig. 1I15B is a schematic representation, taken along the cross-section of the optical assembly shown in Fig. 1I15A, showing the optical path which each PLIB component travels on its way towards a target object to be illuminated;

Fig. 1I15C is a schematic diagram of one of the visible MLLDs employed in the PLIM of Fig. 1I15A, show comprising a multimode laser diode cavity referred to as the active layer (e.g. InGaAsP) having a wide emission-bandwidth over the visible band, a collimating lenslet having a very short focal length, an active mode-locker under switched control (e.g. a temporal-intensity modulator), a passive-mode locker (i.e. saturable absorber) for controlling the pulse-width of the output laser beam, and a mirror which is 99% reflective and 1% transmissive at the operative wavelength of the visible MLLD;

Fig. 1I16A is a perspective view of an optical assembly comprising a PLIA embodying a plurality of visible laser diodes (VLDs), each arranged behind a cylindrical lens, and driven by electrical currents which are modulated by a high-frequency modulation signal so that (i) the transmitted PLIB is temporal intensity modulated according to a temporal intensity modulation function (TIMF) causing the phase along the wavefront of the transmitted PLIB to be modulated, and numerous substantially different speckle-noise patterns produced at image detection array of the IFD Subsystem during the photo-integration time period thereof, so that the numerous time-varying speckle-noise patterns produced at the image detection array can be temporally and spatially averaged during the photo-integration time period thereof, thereby reducing the speckle-noise patterns observed at the image detection array;

Fig. 1I16B is a plan, partial cross-sectional view of the optical assembly shown in Fig. 1I16B;

Fig. 1I17 is a schematic representation of the PLIIM-based system of Fig. 1A embodying a *third* generalized method of reducing the RMS power of observable speckle-noise patterns, wherein the planar laser illumination beam (PLIB) transmitted towards the target object to be illuminated is spatial-intensity modulated by a spatial-intensity modulation function (SIMF), so that the object (e.g. package) is illuminated with spatially coherent-reduced laser beam and, as a result, numerous substantially different time-varying speckle-noise patterns are produced and detected over the photo-integration time period of the image detection array, thereby allowing the numerous speckle-noise patterns to be temporally averaged over the photo-integration time

period and spatially averaged over the image detection element and the RMS power of the observable speckle-noise pattern reduced;

Fig. 1I18A is a schematic representation of the PLIIM-based system of Fig. 1I17, illustrating the *third* generalized speckle-noise pattern reduction method of the present invention applied at the IFD Subsystem employed therein, wherein (i) the transmitted PLIB is spatial-intensity modulated along the planar extent thereof according to a spatial intensity modulation function (SIMF) causing the phase along the wavefront of the PLIB to be modulated and many substantially different time-varying speckle-noise patterns produced at the image detection array of the IFD Subsystem during the photo-integration time period thereof, so that the numerous time-varying speckle-noise patterns produced at the image detection array can be temporally and/or spatially averaged during the photo-integration time period thereof, thereby reducing the RMS power of the speckle-noise pattern observed at the image detection array;

Fig. 1I18B is a high-level flow chart setting forth the primary steps involved in practicing the *third* generalized method of reducing the RMS power of observable speckle-noise patterns in PLIIM-based systems, illustrated in Figs. 1I17 and 1I18A;

Fig. 1I19A is a perspective view of an optical assembly comprising a planar laser illumination array (PLIA) with a refractive-type cylindrical lens array, and an electronically-controlled mechanism for micro-oscillating before the cylindrical lens array, a pair of spatial intensity modulation panels with elements parallelly arranged at a high spatial frequency, having grey-scale transmittance measures, and driven by two pairs of ultrasonic transducers arranged in a push-pull configuration so that transmitted planar laser illumination beam (PLIB) is spatially intensity modulated along the planar extent thereof causing the phase among the wavefront of the transmitted PLIB to be modulated and numerous (i.e. many) substantially different time-varying speckle-noise patterns produced at the image detection array of the IFD Subsystem during the photo-integration time period thereof, and the numerous time-varying speckle-noise patterns produced at the image detection array can be temporally and spatially averaged during the photo-integration time period thereof, thereby reducing the RMS power of the speckle-noise patterns observed at the image detection array;

Fig. 1I19B is a perspective view of the pair of spatial intensity modulation panels employed in the optical assembly shown in Fig. 1I19A;

Fig. 1I19C is a perspective view of the spatial intensity modulation panel support frame employed in the optical assembly shown in Fig. 1I19A;

Fig. 1I19D is a schematic representation of the dual spatial intensity modulation panel structure employed in Fig. 1I19A, shown configured between two pairs of ultrasonic transducers (or flexural elements driven by voice-coil type devices) operated in a push-pull mode of operation, so that at least one spatial intensity modulation panel is constantly moving when the other panel is momentarily stationary during modulation panel direction reversal;

Fig. 1I20 is a schematic representation of the PLIIM-based system of Fig. 1A embodying a *fourth* generalized method of reducing the RMS power of observable speckle-noise patterns, wherein the planar laser illumination beam (PLIB) reflected/scattered from the illuminated object

and received at the IFD Subsystem is spatial-intensity modulated by a spatial-intensity modulation function (SIMF), so that the object (e.g. package) is illuminated with spatially coherent-reduced laser beam and, as a result, numerous substantially different time-varying (random) speckle-noise patterns are produced and detected over the photo-integration time period of the image detection array, thereby allowing the speckle-noise patterns to be temporally averaged over the photo-integration time period and spatially averaged over the image detection element and the observable speckle-noise pattern reduced;

Fig. 1I21A is a schematic representation of the PLIIM-based system of Fig. 1I20, illustrating the *third* generalized speckle-noise pattern reduction method of the present invention applied at the IFD Subsystem employed therein, wherein (i) the transmitted PLIB is spatial-intensity modulated along the planar extent thereof according to a spatial-intensity modulation function (SIMF) causing the phase along the wavefront of the PLIB to be modulated and numerous substantially different time-varying speckle-noise patterns produced at the image detection array of the IFD Subsystem during the photo-integration time period thereof, and the numerous time-varying speckle-noise patterns produced at the image detection array temporally and spatially averaged during the photo-integration time period thereof, thereby reducing the RMS power of the speckle-noise patterns observed at the image detection array;

Fig. 1I21B is a high-level flow chart setting forth the primary steps involved in practicing the *third* generalized method of reducing observable speckle-noise patterns in PLIIM-based systems, illustrated in Figs. 1I20 and 1I21A;

Fig. 1I22A is a schematic representation of a first illustrative embodiment of the PLIIM-basedsystem shown in Fig. 1I20, wherein an electro-optical mechanism is used to generate a rotating maltese-cross aperture (or other spatial intensity modulation plate) disposed before the pupil of the IFD Subsystem, so that the return PLIB is spatial-intensity modulated at the IFD subsystem in accordance with the principles of the present invention;

Fig. 1I22B is a schematic representation of a second illustrative embodiment of the system shown in Fig. 1I20, wherein an electro-mechanical mechanism is used to generate a rotating maltese-cross aperture (or other spatial intensity modulation plate) disposed before the pupil of the IFD Subsystem, so that the return PLIB is spatial-intensity modulated at the IFD subsystem in accordance with the principles of the present invention;

Fig. 1I23 is a schematic representation of the PLIIM-based system of Fig. 1A illustrating the *fifth* generalized method of reducing the RMS power of observable speckle-noise patterns, wherein the planar laser illumination beam (PLIB) reflected/scattered from the illuminated object and received at the IFD Subsystem, is temporal-intensity modulated by a temporal-intensity modulation function (TIMF), so that the target object (e.g. package) is illuminated with temporally coherent-reduced laser beam and, as a result, numerous substantially different time-varying (random) speckle-noise patterns are produced and detected over the photo-integration time period of the image detection array, thereby allowing the speckle-noise patterns to be temporally averaged over the photo-integration time period and spatially averaged over the image detection element and the observable speckle-noise pattern reduced;

Fig. 1I24A is a schematic representation of the PLIIM-based system of Fig. 1I23, illustrating the *fifth* generalized speckle-noise pattern reduction method of the present invention applied at the IFD Subsystem employed therein, wherein (i) the received PLIB is temporal-intensity modulated along the planar extent thereof according to a temporal-intensity modulation (e.g. windowing) function (TIMF) so as to cause the phase along the wavefront of the PLIB to be modulated, and numerous substantially different speckle-noise patterns produced at the image detection array of the IFD Subsystem during the photo-integration time period thereof, and (ii) the numerous time-varying speckle-noise patterns produced at the image detection array temporally and spatially averaged during the photo-integration time period thereof, thereby reducing the RMS power of speckle-noise patterns observed at the image detection array;

Fig. 1I24B is a high-level flow chart setting forth the primary steps involved in practicing the *fifth* generalized method of reducing observable speckle-noise patterns in PLIM-based systems, illustrated in Figs. 1I23 and 1I24A;

Fig. 1I25 is a schematic representation of an illustrative embodiment of the PLIM-based system shown in Fig. 1I23, wherein a high-speed electro-optical temporal intensity modulation panel, mounted before the imaging optics of the IFD subsystem, is used to carry out the temporal-intensity modulation function (TIMF) in accordance with the principles of the present invention;

Fig. 1K1 is a schematic representation illustrating how the field of view of a PLIIM-based system can be fixed to substantially match the scan field width thereof (measured at the top of the scan field) at a substantial distance above a conveyor belt;

Fig. 1K2 is a schematic representation illustrating how the field of view of a PLIIM-based system can be fixed to substantially match the scan field width of a low profile scanning field located slightly above the conveyor belt surface, by fixing the focal length of the imaging subsystem during the optical design stage;

Fig. 1L is a schematic representation illustrating how an arrangement of field of view FOV beam folding mirrors can be used to produce an expanded FOV that matches the geometrical characteristics of the scanning application at hand when the FOV emerges from the system housing;

Fig. 1L2 is a schematic representation illustrating how the fixed field of view (FOV) of an imaging subsystem can be expanded across a working space (e.g. conveyor belt structure) by rotating the FOV during object illumination and imaging operations;

Fig. 1M1 shows a data plot of pixel power density E_{pix} versus. object distance (r) calculated using the arbitrary but reasonable values $E_0 = 1$ W/m^2, f = 80 mm and F = 4.5, demonstrating that, in a counter-intuitive manner, the power density at the pixel (and therefore the power incident on the pixel, as its area remains constant) actually increases as the object distance increases;

Fig. 1M2 is a data plot of laser beam power density versus position along the planar laser beam width showing that the total output power in the planar laser illumination beam of the present invention is distributed along the width of the beam in a roughly Gaussian distribution;

Fig. 1M3 shows a plot of beam width length L versus object distance r calculated using a beam fan/spread angle $\theta = 50°$, demonstrating that the planar laser illumination beam width increases as a function of increasing object distance;

Fig. 1M4 is a typical data plot of planar laser beam height h versus image distance r for a planar laser illumination beam of the present invention focused at the farthest working distance in accordance with the principles of the present invention, demonstrating that the height dimension of the planar laser beam decreases as a function of increasing object distance;

Fig. 1N is a data plot of planar laser beam power density E_0 at the center of its beam width, plotted as a function of object distance, demonstrating that use of the laser beam focusing technique of the present invention, wherein the height of the planar laser illumination beam is decreased as the object distance increases, compensates for the increase in beam width in the planar laser illumination beam, which occurs for an increase in object distance, thereby yielding a laser beam power density on the target object which increases as a function of increasing object distance over a substantial portion of the object distance range of the PLIIM-based system;

Fig. 1O is a data plot of pixel power density E_0 vs. object distance, obtained when using a planar laser illumination beam whose beam height decreases with increasing object distance, and also a data plot of the "reference" pixel power density plot E_{pix} vs. object distance obtained when using a planar laser illumination beam whose beam height is substantially constant (e.g. 1 mm) over the entire portion of the object distance range of the PLIIM-based system;

Fig. 1P1 is a schematic representation of the composite power density characteristics associated with the planar laser illumination array in the PLIIM-based system of Fig. 1G1, taken at the "near field region" of the system, and resulting from the additive power density contributions of the individual visible laser diodes in the planar laser illumination array;

Fig. 1P2 is a schematic representation of the composite power density characteristics associated with the planar laser illumination array in the PLIIM-based system of Fig. 1G1, taken at the "far field region" of the system, and resulting from the additive power density contributions of the individual visible laser diodes in the planar laser illumination array;

Fig. 1Q1 is a schematic representation of second illustrative embodiment of the PLIIM system of the present invention shown in Fig. 1A, shown comprising a linear image formation and detection module, and a pair of planar laser illumination arrays arranged in relation to the image formation and detection module such that the field of view thereof is oriented in a direction that is coplanar with the plane of the stationary planar laser illumination beams produced by the planar laser illumination arrays, without using any laser beam or field of view folding mirrors;

Fig. 1Q2 is a block schematic diagram of the PLIIM-based system shown in Fig. 1Q1, comprising a linear image formation and detection module, a pair of planar laser illumination arrays, an image frame grabber, an image data buffer, an image processing computer, and a camera control computer;

Fig. 1R1 is a schematic representation of third illustrative embodiment of the PLIIM-based system of the present invention shown in Fig. 1A, shown comprising a linear image

formation and detection module having a field of view, a pair of planar laser illumination arrays for producing first and second stationary planar laser illumination beams, and a pair of stationary planar laser beam folding mirrors arranged so as to fold the optical paths of the first and second planar laser illumination beams such that the planes of the first and second stationary planar laser illumination beams are in a direction that is coplanar with the field of view of the image formation and detection module;

Fig. 1R2 is a block schematic diagram of the PLIIM-based system shown in Fig. 1P1, comprising a linear image formation and detection module, a stationary field of view folding mirror, a pair of planar illumination arrays, a pair of stationary planar laser illumination beam folding mirrors, an image frame grabber, an image data buffer, an image processing computer, and a camera control computer;

Fig. 1S1 is a schematic representation of fourth illustrative embodiment of the PLIIM-based system of the present invention shown in Fig. 1A, shown comprising a linear image formation and detection module having a field of view (FOV), a stationary field of view (FOV) folding mirror for folding the field of view of the image formation and detection module, a pair of planar laser illumination arrays for producing first and second stationary planar laser illumination beams, and a pair of stationary planar laser illumination beam folding mirrors for folding the optical paths of the first and second stationary planar laser illumination beams so that planes of first and second stationary planar laser illumination beams are in a direction that is coplanar with the field of view of the image formation and detection module;

Fig. 1S2 is a block schematic diagram of the PLIIM-based system shown in Fig. 1S1, comprising a linear-type image formation and detection module, a stationary field of view folding mirror, a pair of planar laser illumination arrays, a pair of stationary planar laser beam folding mirrors, an image frame grabber, an image data buffer, an image processing computer, and a camera control computer;

Fig. 1T is a schematic representation of an under the-conveyor belt package identification system embodying the PLIIM-based system of Fig. 1A;

Fig. 1U is a schematic representation of a hand-supportable bar code symbol reading system embodying the PLIIM-based system of Fig. 1A;

Fig. 1V1 is a schematic representation of second generalized embodiment of the PLIIM-based system of the present invention, wherein a pair of planar laser illumination arrays (PLIAs) are mounted on opposite sides of a linear type image formation and detection (IDF) module having a field of view, such that the planar laser illumination arrays produce a plane of laser beam illumination (i.e. light) which is disposed substantially coplanar with the field of view of the image formation and detection module, and that the planar laser illumination beam and the field of view of the image formation and detection module move synchronously together while maintaining their coplanar relationship with each other as the planar laser illumination beam and FOV are automatically scanned over a 3-D region of space during object illumination and image detection operations;

Fig. 1V2 is a schematic representation of first illustrative embodiment of the PLIIM-based system of the present invention shown in Fig. 1V1, shown comprising an image formation and detection module having a field of view (FOV), a field of view (FOV) folding/sweeping mirror for folding the field of view of the image formation and detection module, a pair of planar laser illumination arrays for producing first and second planar laser illumination beams, and a pair of planar laser beam folding/sweeping mirrors, jointly or synchronously movable with the FOV folding/sweeping mirror, and arranged so as to fold and sweep the optical paths of the first and second planar laser illumination beams so that the folded field of view of the image formation and detection module is synchronously moved with the planar laser illumination beams in a direction that is coplanar therewith as the planar laser illumination beams are scanned over a 3-D region of space under the control of the camera control computer;

Fig. 1V3 is a block schematic diagram of the PLIIM-based system shown in Fig. 1V1, comprising a pair of planar illumination arrays, a pair of planar laser beam folding/sweeping mirrors, a linear-type image formation and detection module, a field of view folding/sweeping mirror, an image frame grabber, an image data buffer, an image processing computer, and a camera control computer;

Fig. 1V4 is a schematic representation of an over-the-conveyor belt package identification system embodying the PLIIM-based system of Fig. 1V1;

Fig. 1V5 is a schematic representation of a presentation-type bar code symbol reading system embodying the PLIIM-based subsystem of Fig. 1V1;

Fig. 2A is a schematic representation of a third generalized embodiment of the PLIIM-based system of the present invention, wherein a pair of planar laser illumination arrays (PLIAs) are mounted on opposite sides of a linear (i.e. 1-dimensional) type image formation and detection (IFD) module having a fixed focal length imaging lens, a variable focal distance and a fixed field of view (FOV) so that the planar laser illumination arrays produce a plane of laser beam illumination which is disposed substantially coplanar with the field view of the image formation and detection module during object illumination and image detection operations carried out on bar code symbol structures and other graphical indicia which may embody information within its structure;

Fig. 2B1 is a schematic representation of a first illustrative embodiment of the PLIIM-based system shown in Fig. 2A, comprising an image formation and detection module having a field of view (FOV), and a pair of planar laser illumination arrays for producing first and second stationary planar laser illumination beams in an imaging direction that is coplanar with the field of view of the image formation and detection module;

Fig. 2B2 is a schematic representation of the PLIIM-based system of the present invention shown in Fig. 2B1, wherein the linear image formation and detection module is shown comprising a linear array of photo-electronic detectors realized using CCD technology, and each planar laser illumination array is shown comprising an array of planar laser illumination modules;

Fig. 2C1 is a block schematic diagram of the PLIIM-based system shown in Fig. 2B1, comprising a pair of planar illumination arrays, a linear-type image formation and detection module, an image frame grabber, an image data buffer, an image processing computer, and a camera control computer;

Fig. 2C2 is a schematic representation of the linear type image formation and detection module (IFDM) employed in the PLIIM-based system shown in Fig. 2B1, wherein an imaging subsystem having a fixed focal length imaging lens, a variable focal distance and a fixed field of view is arranged on an optical bench, mounted within a compact module housing, and responsive to focus control signals generated by the camera control computer of the PLIIM system;

Fig. 2D1 is a schematic representation of the second illustrative embodiment of the PLIIM system of the present invention shown in Fig. 2A, shown comprising a linear image formation and detection module, a stationary field of view (FOV) folding mirror for folding the field of view of the image formation and detection module, and a pair of planar laser illumination arrays arranged in relation to the image formation and detection module such that the folded field of view is oriented in an imaging direction that is coplanar with the stationary planes of laser illumination produced by the planar laser illumination arrays;

Fig. 2D2 is a block schematic diagram of the PLIIM system shown in Fig. 2D1, comprising a pair of planar laser illumination arrays (PLIAs), a linear-type image formation and detection module, a stationary field of view of folding mirror, an image frame grabber, an image data buffer, an image processing computer, and a camera control computer;

Fig. 2D3 is a schematic representation of the linear type image formation and detection module (IFDM) employed in the PLLIM-based system shown in Fig. 2D1, wherein an imaging subsystem having a fixed focal length imaging lens, a variable focal distance and a fixed field of view is arranged on an optical bench, mounted within a compact module housing, and responsive to focus control signals generated by the camera control computer of the PLIIM-based system;

Fig. 2E1 is a schematic representation of the third illustrative embodiment of the PLIIM-based system of the present invention shown in Fig. 1A, shown comprising an image formation and detection module having a field of view (FOV), a pair of planar laser illumination arrays for producing first and second stationary planar laser illumination beams, a pair of stationary planar laser beam folding mirrors for folding the stationary (i.e. non-swept) planes of the planar laser illumination beams produced by the pair of planar laser illumination arrays, in an imaging direction that is coplanar with the stationary plane of the field of view of the image formation and detection module during system operation;

Fig. 2E2 is a block schematic diagram of the PLIIM-based system shown in Fig. 2B1, comprising a pair of planar laser illumination arrays, a linear image formation and detection module, a pair of stationary planar laser illumination beam folding mirrors, an image frame grabber, an image data buffer, an image processing computer, and a camera control computer;

Fig. 2E3 is a schematic representation of the linear image formation and detection (IFD) module employed in the PLIIM-based system shown in Fig. 2B1, wherein an imaging subsystem having fixed focal length imaging lens, a variable focal distance and a fixed field of view is

arranged on an optical bench, mounted within a compact module housing, and responsive to focus control signals generated by the camera control computer of the PLIIM-based system;

Fig. 2F1 is a schematic representation of the fourth illustrative embodiment of the PLIIM-based system of the present invention shown in Fig. 2A, shown comprising a linear image formation and detection module having a field of view (FOV), a stationary field of view (FOV) folding mirror, a pair of planar laser illumination arrays for producing first and second stationary planar laser illumination beams, and a pair of stationary planar laser beam folding mirrors arranged so as to fold the optical paths of the first and second stationary planar laser illumination beams so that these planar laser illumination beams are oriented in an imaging direction that is coplanar with the folded field of view of the linear image formation and detection module;

Fig. 2F2 is a block schematic diagram of the PLIIM-based system shown in Fig. 2F1, comprising a pair of planar illumination arrays, a linear image formation and detection module, a stationary field of view (FOV) folding mirror, a pair of stationary planar laser illumination beam folding mirrors, an image frame grabber, an image data buffer, an image processing computer, and a camera control computer;

Fig. 2F3 is a schematic representation of the linear-type image formation and detection (IFD) module employed in the PLIIM-based system shown in Fig. 2F1, wherein an imaging subsystem having a fixed focal length imaging lens, a variable focal distance and a fixed field of view is arranged on an optical bench, mounted within a compact module housing, and responsive to focus control signals generated by the camera control computer of the PLIIM-based system;

Fig. 2G is a schematic representation of an over-the-conveyor belt package identification system embodying the PLIIM-based system of Fig. 2A;

Fig. 2H is a schematic representation of a hand-supportable bar code symbol reading system embodying the PLIIM-based system of Fig. 2A;

Fig. 2I1 is a schematic representation of the fourth generalized embodiment of the PLIIM-based system of the present invention, wherein a pair of planar laser illumination arrays (PLIAs) are mounted on opposite sides of a linear image formation and detection (IFD) module having a fixed focal length imaging lens, a variable focal distance and fixed field of view (FOV), so that the planar illumination arrays produces a plane of laser beam illumination which is disposed substantially coplanar with the field view of the image formation and detection module and synchronously moved therewith while the planar laser illumination beams are automatically scanned over a 3-D region of space during object illumination and imaging operations;

Fig. 2I2 is a schematic representation of the first illustrative embodiment of the PLIIM-based system of the present invention shown in Fig. 2I1, shown comprising an image formation and detection (i.e. camera) module having a field of view (FOV), a field of view (FOV) folding/sweeping mirror, a pair of planar laser illumination arrays for producing first and second planar laser illumination beams, and a pair of planar laser beam folding/sweeping mirrors, jointly movable with the FOV folding/sweeping mirror, and arranged so that the field of view of the image formation and detection module is coplanar with the folded planes of first and second

planar laser illumination beams, and the coplanar FOV and planar laser illumination beams are synchronously moved together while the planar laser illumination beams and FOV are scanned over a 3-D region of space containing a stationary or moving bar code symbol or other graphical structure (e.g. text) embodying information;

Fig. 2I3 is a block schematic diagram of the PLIIM-based system shown in Figs. 2I1 and 2I2, comprising a pair of planar illumination arrays, a linear image formation and detection module, a field of view (FOV) folding/sweeping mirror, a pair of planar laser illumination beam folding/sweeping mirrors jointly movable therewith, an image frame grabber, an image data buffer, an image processing computer, and a camera control computer;

Fig. 2I4 is a schematic representation of the linear type image formation and detection (IFD) module employed in the PLIIM-based system shown in Figs. 2I1 and 2I2, wherein an imaging subsystem having a fixed focal length imaging lens, a variable focal distance and a fixed field of view is arranged on an optical bench, mounted within a compact module housing, and responsive to focus control signals generated by the camera control computer of the PLIIM-based system;

Fig. 2I5 is a schematic representation of a hand-supportable bar code symbol reader embodying the PLIIM-based system of Fig. 2I1;

Fig. 2I6 is a schematic representation of a presentation-type bar code symbol reader embodying the PLIIM-based system of Fig. 2I1;

Fig. 3A is a schematic representation of a fifth generalized embodiment of the PLIIM-based system of the present invention, wherein a pair of planar laser illumination arrays (PLIAs) are mounted on opposite sides of a linear image formation and detection (IFD) module having a variable focal length imaging lens, a variable focal distance and a variable field of view, so that the planar laser illumination arrays produce a stationary plane of laser beam illumination (i.e. light) which is disposed substantially coplanar with the field view of the image formation and detection module during object illumination and image detection operations carried out on bar code symbols and other graphical indicia by the PLIIM-based system of the present invention;

Fig. 3B1 is a schematic representation of the first illustrative embodiment of the PLIIM-based system of the present invention shown in Fig. 3A, shown comprising an image formation and detection module, and a pair of planar laser illumination arrays arranged in relation to the image formation and detection module such that the stationary field of view thereof is oriented in an imaging direction that is coplanar with the stationary plane of laser illumination produced by the planar laser illumination arrays, without using any laser beam or field of view folding mirrors.

Fig. 3B2 is a schematic representation of the first illustrative embodiment of the PLIIM-based system shown in Fig. 3B1, wherein the linear image formation and detection module is shown comprising a linear array of photo-electronic detectors realized using CCD technology, and each planar laser illumination array is shown comprising an array of planar laser illumination modules;

Fig. 3C1 is a block schematic diagram of the PLIIM-based shown in Fig. 3B1, comprising a pair of planar laser illumination arrays, a linear image formation and detection module, an image

frame grabber, an image data buffer, an image processing computer, and a camera control computer;

Fig. 3C2 is a schematic representation of the linear type image formation and detection (IFD) module employed in the PLIIM-based system shown in Fig. 3B1, wherein an imaging subsystem having a variable focal length imaging lens, a variable focal distance and a variable field of view is arranged on an optical bench, mounted within a compact module housing, and responsive to zoom and focus control signals generated by the camera control computer of the PLIIM-based system;

Fig. 3D1 is a schematic representation of a first illustrative implementation of the IPD camera subsystem contained in the image formation and detection (IFD) module employed in the PLIIM-based system of Fig. 3B1, shown comprising a stationary lens system mounted before a stationary linear image detection array, a first movable lens system for large stepped movement relative to the stationary lens system during image zooming operations, and a second movable lens system for small stepped movements relative to the first movable lens system and the stationary lens system during image focusing operations;

Fig. 3D2 is an perspective partial view of the second illustrative implementation of the camera subsystem shown in Fig. 3D2, wherein the first movable lens system is shown comprising an electrical rotary motor mounted to a camera body, an arm structure mounted to the shaft of the motor, a slidable lens mount (supporting a first lens group) slidably mounted to a rail structure, and a linkage member pivotally connected to the slidable lens mount and the free end of the arm structure so that, as the motor shaft rotates, the slidable lens mount moves along the optical axis of the imaging optics supported within the camera body;

Fig. 3D3 is an elevated side view of the camera subsystem shown in Fig. 3D2;

Fig. 3E1 is a schematic representation of the second illustrative embodiment of the PLIIM-based system of the present invention shown in Fig. 3A, shown comprising a linear image formation and detection module, a pair of planar laser illumination arrays, and a stationary field of view (FOV) folding mirror arranged in relation to the image formation and detection module such that the stationary field of view thereof is oriented in an imaging direction that is coplanar with the stationary plane of laser illumination produced by the planar laser illumination arrays, without using any planar laser illumination beam folding mirrors;

Fig. 3E2 is a block schematic diagram of the PLIIM-based system shown in Fig. 3E1, comprising a pair of planar illumination arrays, a linear image formation and detection module, a stationary field of view (FOV) folding mirror, an image frame grabber, an image data buffer, an image processing computer, and a camera control computer;

Fig. 3E3 is a schematic representation of the linear type image formation and detection module (IFDM) employed in the PLIIM-based system shown in Fig. 3E1, wherein an imaging subsystem having a variable focal length imaging lens, a variable focal distance and a variable field of view is arranged on an optical bench, mounted within a compact module housing, and responsive to zoom and focus control signals generated by the camera control computer of the PLIIM-based system;

Fig. 3E4 is a schematic representation of an exemplary realization of the PLIIM-based system of Fig. 3E1, shown comprising a compact housing, linear-type image formation and detection (i.e. camera) module, a pair of planar laser illumination arrays, and a field of view (FOV) folding mirror for folding the field of view of the image formation and detection module in a direction that is coplanar with the plane of composite laser illumination beam produced by the planar laser illumination arrays;

Fig. 3E5 is a plan view schematic representation of the PLIIM-based system of Fig. 3E4, taken along line 3E5-3E5 therein, showing the spatial extent of the field of view of the image formation and detection module in the illustrative embodiment of the present invention;

Fig. 3E6 is an elevated end view schematic representation of the PLIIM-based system of Fig. 3E4, taken along line 3E6-3E6 therein, showing the field of view of the linear image formation and detection module being folded in the downwardly imaging direction by the field of view folding mirror, and the planar laser illumination beam produced by each planar laser illumination module being directed in the imaging direction such that both the folded field of view and planar laser illumination beams are arranged in a substantially coplanar relationship during object illumination and imaging operations;

Fig. 3E7 is an elevated side view schematic representation of the PLIIM-based system of Fig. 3E4, taken along line 3E7-3E7 therein, showing the field of view of the linear image formation and detection module being folded in the downwardly imaging direction by the field of view folding mirror, and the planar laser illumination beam produced by each planar laser illumination module being directed along the imaging direction such that both the folded field of view and stationary planar laser illumination beams are arranged in a substantially coplanar relationship during object illumination and image detection operations;

Fig. 3E8 is an elevated side view of the PLIIM-based system of Fig. 3E4, showing the spatial limits of the variable field of view (FOV) of its linear image formation and detection module when controllably adjusted to image the tallest packages moving on a conveyor belt structure, as well as the spatial limits of the variable FOV of the linear image formation and detection module when controllably adjusted to image objects having height values close to the surface height of the conveyor belt structure;

Fig. 3F1 is a schematic representation of the third illustrative embodiment of the PLIIM-based system of the present invention shown in Fig. 3A, shown comprising a linear image formation and detection module having a field of view (FOV), a pair of planar laser illumination arrays for producing first and second stationary planar laser illumination beams, a pair of stationary planar laser illumination beam folding mirrors arranged relative to the planar laser illumination arrays so as to fold the stationary planar laser illumination beams produced by the pair of planar illumination arrays in an imaging direction that is coplanar with stationary field of view of the image formation and detection module during illumination and imaging operations;

Fig. 3F2 is a block schematic diagram of the PLIIM-based system shown in Fig. 3FF1, comprising a pair of planar illumination arrays, a linear image formation and detection module, a

pair of stationary planar laser illumination beam folding mirrors, an image frame grabber, an image data buffer, an image processing computer, and a camera control computer;

Fig. 3F3 is a schematic representation of the linear type image formation and detection module (IFDM) employed in the PLIIM-based system shown in Fig. 3F1, wherein an imaging subsystem having a variable focal length imaging lens, a variable focal distance and a variable field of view is arranged on an optical bench, mounted within a compact module housing, and is responsive to zoom and focus control signals generated by the camera control computer of the PLIIM-based system during illumination and imaging operations;

Fig. 3G1 is a schematic representation of the fourth illustrative embodiment of the PLIIM-based system of the present invention shown in Fig. 3A, shown comprising a linear image formation and detection (i.e. camera) module having a field of view (FOV), a pair of planar laser illumination arrays for producing first and second stationary planar laser illumination beams, a stationary field of view (FOV) folding mirror for folding the field of view of the image formation and detection module, and a pair of stationary planar laser beam folding mirrors arranged so as to fold the optical paths of the first and second planar laser illumination beams such that stationary planes of first and second planar laser illumination beams are in an imaging direction which is coplanar with the field of view of the image formation and detection module during illumination and imaging operations;

Fig. 3G2 is a block schematic diagram of the PLIIM system shown in Fig. 3G1, comprising a pair of planar illumination arrays, a linear image formation and detection module, a stationary field of view (FOV) folding mirror, a pair of stationary planar laser illumination beam folding mirrors, an image frame grabber, an image data buffer, an image processing computer, and a camera control computer;

Fig. 3G3 is a schematic representation of the linear type image formation and detection module (IFDM) employed in the PLIIM-based system shown in Fig. 3G1, wherein an imaging subsystem having a variable focal length imaging lens, a variable focal distance and a variable field of view is arranged on an optical bench, mounted within a compact module housing, and responsive to zoom and focus control signals generated by the camera control computer of the PLIIM system during illumination and imaging operations;

Fig. 3H is a schematic representation of over-the-conveyor and side-of conveyor belt package identification systems embodying the PLIIM-based system of Fig. 3A;

Fig. 3I is a schematic representation of a hand-supportable bar code symbol reading device embodying the PLIIM-based system of Fig. 3A;

Fig. 3J1 is a schematic representation of the sixth generalized embodiment of the PLIIM-based system of the present invention, wherein a pair of planar laser illumination arrays (PLIAs) are mounted on opposite sides of a linear image formation and detection (IFD) module having a variable focal length imaging lens, a variable focal distance and a variable field of view, so that the planar illumination arrays produce a plane of laser beam illumination which is disposed substantially coplanar with the field view of the image formation and detection module and

synchronously moved therewith as the planar laser illumination beams are scanned across a 3-D region of space during object illumination and image detection operations;

Fig. 3J2 is a schematic representation of the first illustrative embodiment of the PLIIM-based system of the present invention shown in Fig. 3J1, shown comprising an image formation and detection module having a field of view (FOV), a pair of planar laser illumination arrays for producing first and second planar laser illumination beams, a field of view folding/sweeping mirror for folding and sweeping the field of view of the image formation and detection module, and a pair of planar laser beam folding/sweeping mirrors jointly movable with the FOV folding/sweeping mirror and arranged so as to fold the optical paths of the first and second planar laser illumination beams so that the field of view of the image formation and detection module is in an imaging direction that is coplanar with the planes of first and second planar laser illumination beams during illumination and imaging operations;

Fig. 3J3 is a block schematic diagram of the PLIIM-based system shown in Fig. 3J1 and 3J2, comprising a pair of planar illumination arrays, a linear image formation and detection module, a field of view folding/sweeping mirror, a pair of planar laser illumination beam folding/sweeping mirrors, an image frame grabber, an image data buffer, an image processing computer, and a camera control computer;

Fig. 3J4 is a schematic representation of the linear type image formation and detection (IFD) module employed in the PLIIM-based system shown in Figs. 3J1 and J2, wherein an imaging subsystem having a variable focal length imaging lens, a variable focal distance and a variable field of view is arranged on an optical bench, mounted within a compact module housing, and responsive to zoom and focus control signals generated by the camera control computer of the PLIIM system during illumination and imaging operations;

Fig. 3J5 is a schematic representation of a hand-held bar code symbol reading system embodying the PLIIM-based subsystem of Fig. 3J1;

Fig. 3J6 is a schematic representation of a presentation-type hold-under bar code symbol reading system embodying the PLIIM subsystem of Fig. 3J1;

Fig. 4A is a schematic representation of a seventh generalized embodiment of the PLIIM-based system of the present invention, wherein a pair of planar laser illumination arrays (PLIAs) are mounted on opposite sides of an area (i.e. 2-dimensional) type image formation and detection module (IFDM) having a fixed focal length camera lens, a fixed focal distance and fixed field of view projected through a 3-D scanning region, so that the planar laser illumination arrays produce a plane of laser illumination which is disposed substantially coplanar with sections of the field view of the image formation and detection module while the planar laser illumination beam is automatically scanned across the 3-D scanning region during object illumination and imaging operations carried out on a bar code symbol or other graphical indicia by the PLIIM-based system;

Fig. 4B1 is a schematic representation of the first illustrative embodiment of the PLIIM-based system of the present invention shown in Fig. 4A, shown comprising an arean image formation and detection module having a field of view (FOV) projected through a 3-D scanning region, a

pair of planar laser illumination arrays for producing first and second planar laser illumination beams, and a pair of planar laser beam folding/sweeping mirrors for folding and sweeping the planar laser illumination beams so that the optical paths of these planar laser illumination beams are oriented in an imaging direction that is coplanar with a section of the field of view of the image formation and detection module as the planar laser illumination beams are swept through the 3-D scanning region during object illumination and imaging operations;

Fig. 4B2 is a schematic representation of PLIIM-based system shown in Fig. 4B1, wherein the linear image formation and detection module is shown comprising an area (2-D) array of photo-electronic detectors realized using CCD technology, and each planar laser illumination array is shown comprising an array of planar laser illumination modules (PLIMs);

Fig. 4B3 is a block schematic diagram of the PLIIM-based system shown in Fig. 4B1, comprising a pair of planar illumination arrays, an area-type image formation and detection module, a pair of planar laser illumination beam sweeping mirrors, an image frame grabber, an image data buffer, an image processing computer, and a camera control computer;

Fig. 4C1 is a schematic representation of the second illustrative embodiment of the PLIIM system of the present invention shown in Fig. 4A, comprising a arean image formation and detection module having a field of view (FOV), a pair of planar laser illumination arrays for producing first and second planar laser illumination beams, a stationary field of view folding mirror for folding and projecting the field of view through a 3-D scanning region, and a pair of planar laser beam folding/sweeping mirrors for folding and sweeping the planar laser illumination beams so that the optical paths of these planar laser illumination beams are oriented in an imaging direction that is coplanar with a section of the field of view of the image formation and detection module as the planar laser illumination beams are swept through the 3-D scanning region during object illumination and imaging operations;

Fig. 4C2 is a block schematic diagram of the PLIIM-based system shown in Fig. 4C1, comprising a pair of planar illumination arrays, an area-type image formation and detection module, a movable field of view folding mirror, a pair of planar laser illumination beam sweeping mirrors jointly or otherwise synchronously movable therewith, an image frame grabber, an image data buffer, an image processing computer, and a camera control computer;

Fig. 4D is a schematic representation of presentation-type holder-under bar code symbol reading system embodying the PLIIM-based subsystem of Fig. 4A;

Fig. 4E is a schematic representation of hand-supportable-type bar code symbol reading system embodying the PLIIM-based subsystem of Fig. 4A;

Fig. 5A is a schematic representation of an eighth generalized embodiment of the PLIIM-based system of the present invention, wherein a pair of planar laser illumination arrays (PLIAs) are mounted on opposite sides of an area (i.e. 2-D) type image formation and detection (IFD) module having a fixed focal length imaging lens, a variable focal distance and a fixed field of view (FOV) projected through a 3-D scanning region, so that the planar laser illumination arrays produce a plane of laser beam illumination which is disposed substantially coplanar with sections of the field view of the image formation and detection module as the planar laser illumination

beams are automatically scanned through the 3-D scanning region during object illumination and image detection operations carried out on a bar code symbol or other graphical indicia by the PLIIM-based system;

Fig. 5B1 is a schematic representation of the first illustrative embodiment of the PLIIM-based system shown in Fig. 5A, shown comprising an image formation and detection module having a field of view (FOV) projected through a 3-D scanning region, a pair of planar laser illumination arrays for producing first and second planar laser illumination beams, and a pair of planar laser beam folding/sweeping mirrors for folding and sweeping the planar laser illumination beams so that the optical paths of these planar laser illumination beams are oriented in an imaging direction that is coplanar with a section of the field of view of the image formation and detection module as the planar laser illumination beams are swept through the 3-D scanning region during object illumination and imaging operations;

Fig. 5B2 is a schematic representation of the first illustrative embodiment of the PLIIM-based system shown in Fig. 5B1, wherein the linear image formation and detection module is shown comprising an area (2-D) array of photo-electronic detectors realized using CCD technology, and each planar laser illumination array is shown comprising an array of planar laser illumination modules;

Fig. 5B3 is a block schematic diagram of the PLIIM-based system shown in Fig. 5B1, comprising a short focal length imaging lens, a low-resolution image detection array and associated image frame grabber, a pair of planar illumination arrays, a high-resolution area-type image formation and detection module, a pair of planar laser beam folding/sweeping mirrors, an associated image frame grabber, an image data buffer, an image processing computer, and a camera control computer;

Fig. 5B4 is a schematic representation of the area-type image formation and detection (IFD) module employed in the PLIIM-based system shown in Fig. 5B1, wherein an imaging subsystem having a fixed length imaging lens, a variable focal distance and fixed field of view is arranged on an optical bench, mounted within a compact module housing, and responsive to focus control signals generated by the camera control computer of the PLIIM-based system during illumination and imaging operations;

Fig. 5C1 is a schematic representation of the second illustrative embodiment of the PLIIM-based system of the present invention shown in Fig. 5A, shown comprising an image formation and detection module, a stationary FOV folding mirror for folding and projecting the FOV through a 3-D scanning region, a pair of planar laser illumination arrays, and pair of planar laser beam folding/sweeping mirrors for folding and sweeping the planar laser illumination beams so that the optical paths of these planar laser illumination beams are oriented in an imaging direction that is coplanar with a section of the field of view of the image formation and detection module as the planar laser illumination beams are swept through the 3-D scanning region during object illumination and imaging operations;

Fig. 5C2 is a schematic representation of the second illustrative embodiment of the PLIIM-based system shown in Fig. 5A, wherein the linear image formation and detection module is shown

comprising an area (2-D) array of photo-electronic detectors realized using CCD technology, and each planar laser illumination array is shown comprising an array of planar laser illumination modules;

Fig. 5C3 is a block schematic diagram of the PLIIM-based system shown in Fig. 5C1, comprising a pair of planar illumination arrays, an area-type image formation and detection module, a stationary field of view (FOV) folding mirror, a pair of planar laser illumination beam folding and sweeping mirrors, an image frame grabber, an image data buffer, an image processing computer, and a camera control computer;

Fig. 5C4 is a schematic representation of the area-type image formation and detection (IFD) module employed in the PLIIM-based system shown in Fig. 5C1, wherein an imaging subsystem having a fixed length imaging lens, a variable focal distance and fixed field of view is arranged on an optical bench, mounted within a compact module housing, and responsive to focus control signals generated by the camera control computer of the PLIIM-based system during illumination and imaging operations;

Fig. 5D is a schematic representation of a presentation-type hold-under bar code symbol reading system embodying the PLIIM-based subsystem of Fig. 5A;

Fig. 6A is a schematic representation of a ninth generalized embodiment of the PLIIM-based system of the present invention, wherein a pair of planar laser illumination arrays (PLIAs) are mounted on opposite sides of an area type image formation and detection module (IFDM) having a variable focal length imaging lens, a variable focal distance and variable field of view projected through a 3-D scanning region, so that the planar laser illumination arrays produce a plane of laser beam illumination which is disposed substantially coplanar with sections of the field view of the image formation and detection module as the planar laser illumination beams are automatically scanned through the 3-D scanning region during object illumination and image detection operations carried out on a bar code symbol or other graphical indicia by the PLIIM-based system;

Fig. 6B1 is a schematic representation of the first illustrative embodiment of the PLIIM-based system of the present invention shown in Fig. 6A, shown comprising an image formation and detection module, a pair of planar laser illumination arrays for producing first and second planar laser illumination beams, a pair of planar laser illumination arrays for producing first and second planar laser illumination beams, and a pair of planar laser beam folding/sweeping mirrors for folding and sweeping the planar laser illumination beams so that the optical paths of these planar laser illumination beams are oriented in an imaging direction that is coplanar with a section of the field of view of the image formation and detection module as the planar laser illumination beams are swept through the 3-D scanning region during object illumination and imaging operations;

Fig. 6B2 is a schematic representation of a first illustrative embodiment of the PLIIM-based system shown in Fig. 6B1, wherein the arean image formation and detection module is shown comprising an area array of photo-electronic detectors realized using CCD technology, and each

planar laser illumination array is shown comprising an array of planar laser illumination modules;

Fig. 6B3 is a schematic representation of the first illustrative embodiment of the PLIIM-based system of the present invention shown in Fig. 6B1, shown comprising a pair of planar illumination arrays, an area-type image formation and detection module, a pair of planar laser beam folding/sweeping mirrors, an image frame grabber, an image data buffer, an image processing computer, and a camera control computer;

Fig. 6B4 is a schematic representation of the area-type (2-D) image formation and detection (IFD) module employed in the PLIIM system shown in Fig. 6B1, wherein an imaging subsystem having a variable length imaging lens, a variable focal distance and variable field of view is arranged on an optical bench, mounted within a compact module housing, and responsive to zoom and focus control signals generated by the camera control computer of the PLIIM system during illumination and imaging operations;

Fig. 6C1 is a schematic representation of the second illustrative embodiment of the PLIIM-based system of the present invention shown in Fig. 6A, shown comprising an image formation and detection module, a stationary FOV folding mirror for folding and projecting the FOV through a 3-D scanning region, a pair of planar laser illumination arrays, and pair of planar laser beam folding/sweeping mirrors for folding and sweeping the planar laser illumination beams so that the optical paths of these planar laser illumination beams are oriented in an imaging direction that is coplanar with a section of the field of view of the image formation and detection module as the planar laser illumination beams are swept through the 3-D scanning region during object illumination and imaging operations;

Fig. 6C2 is a schematic representation of a second illustrative embodiment of the PLIIM-based system shown in Fig. 6C1, wherein the arean image formation and detection module is shown comprising an area array of photo-electronic detectors realized using CCD technology, and each planar laser illumination array is shown comprising an array of planar laser illumination modules;

Fig. 6C3 is a schematic representation of the second illustrative embodiment of the PLIIM-based system of the present invention shown in Fig. 6C1, shown comprising a pair of planar illumination arrays, an area-type image formation and detection module, a stationary field of view (FOV) folding mirror, a pair of planar laser illumination beam folding and sweeping mirrors, an image frame grabber, an image data buffer, an image processing computer, and a camera control computer;

Fig. 6C4 is a schematic representation of the area-type image formation and detection (IFD) module employed in the PLIIM system shown in Fig. 5C1, wherein an imaging subsystem having a variable length imaging lens, a variable focal distance and variable field of view is arranged on an optical bench, mounted within a compact module housing, and responsive to zoom and focus control signals generated by the camera control computer of the PLIIM-based system during illumination and imaging operations;

Fig. 6C5 is a schematic representation of a presentation type hold-under bar code symbol reading system embodying the PLIIM-based system of Fig. 6A;

Fig. 6D1 is a schematic representation of an exemplary realization of the PLIIM-based system of Fig. 6A, shown comprising an image formation and detection module, a stationary field of view (FOV) folding mirror for folding and projecting the FOV through a 3-D scanning region, a pair of planar laser illumination arrays, and pair of planar laser beam folding/sweeping mirrors for folding and sweeping the planar laser illumination beams so that the optical paths of these planar laser illumination beams are oriented in an imaging direction that is coplanar with a section of the field of view of the image formation and detection module as the planar laser illumination beams are swept through the 3-D scanning region during object illumination and imaging operations;

Fig. 6D2 is a plan view schematic representation of the PLIIM-based system of Fig. 6D1, taken along line 6D2-6D2 in Fig. 6D1, showing the spatial extent of the field of view of the image formation and detection module in the illustrative embodiment of the present invention;

Fig. 6D3 is an elevated end view schematic representation of the PLIIM-based system of Fig. 6D1, taken along line 6D3-6D3 therein, showing the FOV of the arean image formation and detection module being folded by the stationary FOV folding mirror and projected downwardly through a 3-D scanning region, and the planar laser illumination beams produced from the planar laser illumination arrays being folded and swept so that the optical paths of these planar laser illumination beams are oriented in a direction that is coplanar with a section of the FOV of the image formation and detection module as the planar laser illumination beams are swept through the 3-D scanning region during object illumination and imaging operations;

Fig. 6D4 is an elevated side view schematic representation of the PLIIM-based system of Fig. 6D1, taken along line 6D4-6D4 therein, showing the FOV of the arean image formation and detection module being folded and projected downwardly through the 3-D scanning region, while the planar laser illumination beams are swept through the 3-D scanning region during object illumination and imaging operations;

Fig. 6D5 is an elevated side view of the PLIIM-based system of Fig. 6D1, showing the spatial limits of the variable field of view (FOV) provided by the arean image formation and detection module when imaging the tallest package moving on a conveyor belt structure must be imaged, as well as the spatial limits of the FOV of the image formation and detection module when imaging objects having height values close to the surface height of the conveyor belt structure;

Fig. 6E1 is a schematic representation of a tenth generalized embodiment of the PLIIM-based system of the present invention, wherein a 3-D field of view and a pair of planar laser illumination beams are controllably steered about a 3-D scanning region;

Fig. 6E2 is a schematic representation of the PLIIM-based system shown in Fig. 6E1, shown comprising an area-type (2D) image formation and detection module, a pair of planar laser illumination arrays, a pair of x and y axis field of view (FOV) folding mirrors arranged in relation to the image formation and detection module, and a pair of planar laser illumination

beam sweeping mirrors arranged in relation to the pair of planar laser beam illumination mirrors, such that the planes of laser illumination are coplanar with a planar section of the 3-D field of view of the image formation and detection module as the planar laser illumination beams are automatically scanned across a 3-D region of space during object illumination and image detection operations;

Fig. 6E3 is a schematic representation of the PLIIM-based system shown in Fig. 6E1, shown, comprising an image formation and detection module, a pair of planar laser illumination arrays, a pair of x and y axis FOV folding mirrors arranged in relation to the image formation and detection module, and a pair planar laser illumination beam sweeping mirrors arranged in relation to the pair of planar laser beam illumination mirrors, an image frame grabber, an image data buffer, an image processing computer, and a camera control computer;

Fig. 6E4 is a schematic representation showing a portion of the PLIIM-based system in Fig. 6E1, wherein the 3-D field of view of the image formation and detection module is steered over the 3-D scanning region of the system using the x and y axis FOV folding mirrors, working in cooperation with the planar laser illumination beam folding mirrors which sweep the pair of planar laser illumination beams in accordance with the principles of the present invention;

Fig. 7A is a schematic representation of a first illustrative embodiment of the hybrid holographic/CCD-based PLIIM system of the present invention, wherein (i) a pair of planar laser illumination arrays are used to generate a composite planar laser illumination beam for illuminating a target object, (ii) a holographic-type cylindrical lens is used to collimate the rays of the planar laser illumination beam down onto the a conveyor belt surface, and (iii) a motor-driven holographic imaging disc, supporting a plurality of transmission-type volume holographic optical elements (HOE) having different focal lengths, is disposed before a linear (1-D) CCD image detection array, and functions as a variable-type imaging subsystem capable of detecting images of objects over a large range of object (i.e. working) distances while the planar laser illumination beam illuminates the target object;

Fig. 7B is an elevated side view of the hybrid holographic/CCD-based PLIIM system of Fig. 7A, showing the coplanar relationship between the planar laser illumination beam(s) produced by the planar laser illumination arrays of the PLIIM system, and the variable field of view (FOV) produced by the variable holographic-based focal length imaging subsystem of the PLIIM system;

Fig. 8A is a schematic representation of a second illustrative embodiment of the hybrid holographic/CCD-based PLIIM system of the present invention, wherein (i) a pair of planar laser illumination arrays are used to generate a composite planar laser illumination beam for illuminating a target object, (ii) a holographic-type cylindrical lens is used to collimate the rays of the planar laser illumination beam down onto the a conveyor belt surface, and (iii) a motor-driven holographic imaging disc, supporting a plurality of transmission-type volume holographic optical elements (HOE) having different focal lengths, is disposed before an area (2-D) CCD image detection array, and functions as a variable-type imaging subsystem capable of detecting

images of objects over a large range of object (i.e. working) distances while the planar laser illumination beam illuminates the target object;

Fig. 8B is an elevated side view of the hybrid holographic/CCD-based PLIIM system of Fig. 8A, showing the coplanar relationship between the planar laser illumination beam(s) produced by the planar laser illumination arrays of the PLIIM system, and the variable field of view (FOV) produced by the variable holographic-based focal length imaging subsystem of the PLIIM system;

Fig. 9 is a perspective view of a first illustrative embodiment of the unitary, intelligent, package identification and dimensioning of the present invention, wherein packages, arranged in a singulated or non-singulated configuration, are transported along a high-speed conveyor belt, detected and dimensioned by the LADAR-based imaging, detecting and dimensioning subsystem of the present invention, weighed by an electronic weighing scale, and identified by an automatic PLIIM-based bar code symbol reading system employing a 1-D (i.e. linear) CCD-based scanning array, below which a variable focus imaging lens is mounted for imaging bar coded packages transported therebeneath in a fully automated manner;

Fig. 10 is a schematic block diagram illustrating the system architecture and subsystem components of the unitary package identification and dimensioning system of Fig. 9, shown comprising a LADAR-based package imaging, detecting and dimensioning subsystem (with its integrated package velocity computation subsystem, package height/width/length profiling subsystem, the package-in-tunnel indication subsystem, a package-out-of-tunnel indication subsystem), a PLIIM-based (linear CCD) bar code symbol reading subsystem, data-element queuing, handling and processing subsystem, the input/output port multiplexing subsystem, an I/O port for a graphical user interface (GUI), network interface controller (for supporting networking protocols such as Ethernet, IP, etc.), all of which are integrated together as a fully working unit contained within a single housing of ultra-compact construction;

Fig. 11 is a schematic representation of a portion of the unitary PLIIM-based package identification and dimensioning system of Fig. 9, showing in greater detail the interface between its PLIIM-based subsystem and LDIP subsystem, and the various information signals which are generated by the LDIP subsystem and provided to the camera control computer, and how the camera control computer generates digital camera control signals which are provided to the image formation and detection (i.e. camera) subsystem so that the unitary system can carry out its diverse functions in an integrated manner, including (1) capturing digital images having (i) square pixels (i.e. 1:1 aspect ratio) independent of package height or velocity, (ii) significantly reduced speckle-noise pattern levels, and (iii) constant image resolution measured in dots per inch (dpi) independent of package height or velocity and without the use of costly telecentric optics employed by prior art systems, (2) automatic cropping of captured images so that only regions of interest reflecting the package or package label are transmitted to the image processing computer (for 1-D or 2-D bar code symbol decoding or optical character recognition (OCR) image processing), and (3) automatic image lifting operations for supporting other package management operations carried out by the end-user;

Fig. 12A is a perspective view of the housing for the unitary package dimensioning and identification system of Fig. 9, showing the construction of its housing and the spatial arrangement of its two optically-isolated compartments, with all internal parts removed therefrom for purposes of illustration;

Fig. 12B is a cross-sectional view of the unitary PLM-based package dimensioning and identification system of Fig. 9, taken along the line 12A-12A therein, showing the PLIIM-based subsystem and subsystem components contained within a first optically-isolated compartment formed in the upper deck of the unitary system housing, and the LDIP subsystem contained within a second optically-isolated compartment formed in the lower deck, below the first optically-isolated compartment;

Fig. 12C is a cross-sectional view of the unitary package dimensioning and identification system of Fig. 9, taken along line 12C-12C therein, showing the spatial layout of the various optical and electro-optical components mounted on the optical bench of the PLIIM-based subsystem installed within the first optically-isolated cavity of the system housing;

Fig. 12D is a cross-sectional view of the unitary PLIIM-based package dimensioning and identification system of Fig. 9, taken along line 12D-12D therein, showing the spatial layout of the various optical and electro-optical components mounted on the optical bench of the LDIP subsystem installed within the second optically-isolated cavity of the system housing;

Fig. 12E is a schematic representation of an illustrative implementation of the image formation and detection subsystem contained in the image formation and detection (IFD) module employed in the PLIIM-based system of Fig. 9, shown comprising a stationary lens system mounted before the stationary linear (CCD-type) image detection array, a first movable lens system for stepped movement relative to the stationary lens system during image zooming operations, and a second movable lens system for stepped movements relative to the first movable lens system and the stationary lens system during image focusing operations;

Fig. 13A is a first perspective view of an alternative housing design for use with the unitary PLIIM-based package identification and dimensioning subsystem of the present invention, wherein the housing has the same light transmission apertures provided in the housing design shown in Figs. 12A and 12B, but has no housing panels disposed about the light transmission apertures through which planar laser illumination beams and the field of view of the PLIIM-based subsystem extend, thereby providing a region of space into which an optional device can be mounted for carrying out a speckle-noise reduction solution in accordance with the principles of the present invention;

Fig. 13B is a second perspective view of the housing design shown in Fig.13A;

Fig. 13C is a third perspective view of the housing design shown in Fig. 13A, showing the different sets of optically-isolated light transmission apertures formed in the underside surface of the housing;

Fig. 14 is a schematic representation of the unitary PLIIM-based package dimensioning and identification system of Fig. 13, showing the use of a "Real-Time" Package Height Profiling And Edge Detection Processing Module within the LDIP subsystem to automatically process raw

data received by the LDIP subsystem and generate, as output, time-stamped data sets that are transmitted to a camera control computer which automatically processes the received time-stamped data sets and generates real-time camera control signals that drive the focus and zoom lens group translators within a high-speed auto-focus/auto-zoom digital camera subsystem includes a module (i.e. the IFD module) so that the camera subsystem automatically captures digital images having (1) square pixels (i.e. 1:1 aspect ratio) independent of package height or velocity, (2) significantly reduced speckle-noise levels, and (3) constant image resolution measured in dots per inch (dpi) independent of package height or velocity;

Fig. 15 is a flow chart describing the primary data processing operations that are carried out by the Real-Time Package Height Profile And Edge Detection Processing Module within the LDIP subsystem employed in the PLIIM-based system shown in Figs. 13 and 14, wherein each sampled row of raw range data collected by the LDIP subsystem is processed to produce a data set (i.e.containing data elements representative of the current time-stamp, the package height, the position of the left and right edges of the package edges, the coordinate subrange where height values exhibit maximum range intensity variation and the current package velocity) which is then transmitted to the camera control computer for processing and generation of real-time camera control signals that are transmitted to the auto-focus/auto-zoom digital camera subsystem;

Fig. 16 is a flow chart describing the primary data processing operations that are carried out by the Real-Time Package Edge Detection Processing Method performed by the Real-Time Package Height Profiling And Edge Detection Processing Module within the LDIP subsystem of PLIIM-based system shown in Figs. 13 and 14;

Fig. 17 is a schematic representation of the LDIP Subsystem embodied in the unitary PLIIM-based subsystem of Figs. 13 and 14, shown mounted above a conveyor belt structure;

Fig. 17A is a data structure used in the Real-Time Package Height Profiling Method of Fig. 15 to buffer sampled range intensity (I_i) and phase angle (i) data samples collected by LDIP Subsystem during each LDIP scan cycle and before application of coordinate transformations;

Fig. 17B is a data structure used in the Real-Time Package Edge Detection Method of Fig. 16; to buffer range (R_i) and polar angle ($Ø_i$) dated samples collected by the LDIP Subsystem during each LDIP scan cycle, and before application of coordinate transformations;

Fig. 17C is a data structure used in the method of Fig. 15 to buffer package height (y_i) and position (x_i) data samples computed by the LDIP subsystem during each LDIP scan cycle, and after application of coordinate transformations;

Figs. 18A and 18B, taken together, set forth a Real-Time Camera Control Process that is carried out within the camera control computer employed within the PLIIM-based systems of Fig. 11, wherein the Camera Control (Computer) Subsystem automatically processes the received time-stamped data sets and generates real-time camera control signals that drive the focus and zoom lens group translators within a high-speed Auto-Focus/Auto-Zoom Digital Camera Subsystem (i.e. the IFD module) so that the camera subsystem automatically captures digital images having (1) square pixels (i.e. 1:1 aspect ratio) independent of package height or

velocity, (2) significantly reduced speckle-noise levels, and (3) constant image resolution measured in dots per inch (DPI) independent of package height or velocity;

Fig. 19 is a schematic representation of the Package Data Buffer structure employed by the Real-Time Package Height Profiling And Edge Detection Processing Module illustrated in Fig. 14, wherein each current raw data set received by the Real-Time Package Height Profiling And Edge Detection Processing Module is buffered in a row of the Package Data Buffer, and each data element in the raw data set is assigned a fixed column index and variable row index which increments as the raw data set is shifted one index unit as each new incoming raw data set is received into the Package Data Buffer;

Fig. 20. is a schematic representation of the Camera Pixel Data Buffer structure employed by the Auto-Focus/Auto-Zoom Digital Camera Subsystem shown in Fig. 14, wherein each pixel element in each captured image frame is stored in a storage cell of the Camera Pixel Data Buffer, which is assigned a unique set of pixel indices (i,j);

Fig. 21 is a schematic representation of an exemplary Zoom and Focus Lens Group Position Look-Up Table associated with the Auto-Focus/Auto-Zoom Digital Camera Subsystem used by the camera control computer of the illustrative embodiment, wherein for a given package height detected by the Real-Time Package Height Profiling And Edge Detection Processing Module, the camera control computer uses the Look-Up Table to determine the precise positions to which the focus and zoom lens groups must be moved by generating and supplying real-time camera control signals to the focus and zoom lens group translators within a high-speed Auto-Focus/Auto-Zoom Digital Camera Subsystem (i.e. the IFD module) so that the camera subsystem automatically captures focused digital images having (1) square pixels (i.e. 1:1 aspect ratio) independent of package height or velocity, (2) significantly reduced speckle-noise levels, and (3) constant image resolution measured in dots per inch (DPI) independent of package height or velocity;

Fig. 22 is a graphical representation of the focus and zoom lens movement characteristics associated with the zoom and lens groups employed in the illustrative embodiment of the Auto-Focus/Auto-Zoom Digital Camera Subsystem, wherein for a given detected package height, the position of the focus and zoom lens group relative to the Camera's working distance is obtained by finding the points along these characteristics at the specified working distance (i.e. detected package height);

Fig. 23 is a schematic representation of an exemplary Photo-integration Time Period Look-Up Table associated with CCD image detection array employed in the Auto-Focus/Auto-Zoom Digital Camera Subsystem of the PLIIM-based system, wherein for a given detected package height and package velocity, the camera control computer uses the Look-Up Table to determine the precise photo-integration time period for the CCD image detection elements employed within the Auto-Focus/Auto-Zoom Digital Camera Subsystem (i.e. the IFD module) so that the camera (i.e. IFD) subsystem automatically captures focused digital images having (1) square pixels (i.e. 1:1 aspect ratio) independent of package height or velocity, (2) significantly

reduced speckle-noise levels, and (3) constant image resolution measured in dots per inch (DPI) independent of package height or velocity;

Fig. 24 is a perspective view of a unitary, intelligent, package identification and dimensioning system constructed in accordance with the second illustrated embodiment of the present invention, wherein packages, arranged in a non-singulated or singulated configuration, are transported along a high speed conveyor belt, detected and dimensioned by the LADAR-based imaging, detecting and dimensioning subsystem of the present invention, weighed by a weighing scale, and identified by an automatic PLIIM-based bar code symbol reading system employing a 2-D (i.e. area) CCD-based scanning arra,y below which a light focusing lens is mounted for imaging bar coded packages transported therebeneath and decode processing these images to read such bar code symbols in a fully automated manner without human intervention;

Fig. 25 is a schematic block diagram illustrating the system architecture and subsystem components of the unitary package identification and dimensioning system shown in Fig. 24, namely its LADAR-based package imaging, detecting and dimensioning subsystem (with its integrated package velocity computation subsystem, package height/width/length profiling subsystem, the package-in-tunnel indication subsystem, the package-out-of-tunnel indication subsystem), the PLIIM-based (linear CCD) bar code symbol reading subsystem, the data-element queuing, handling and processing subsystem, the input/output port multiplexing subsystem, an I/O port for a graphical user interface (GUI), and network interface controller (for supporting networking protocols such as Ethernet, IP, etc.), all of which are integrated together as a working unit contained within a single housing of ultra-compact construction;

Fig. 26 is a schematic representation of a portion of the unitary package identification and dimensioning system of Fig. 24 showing in greater detail the interface between its PLIIM-based subsystem and LDIP subsystem, and the various information signals which are generated by the LDIP subsystem and provided to the camera control computer, and how the camera control computer generates digital camera control signals which are provided to the image formation and detection (IFD) subsystem (i.e. "camera") so that the unitary system can carry out its diverse functions in an integrated manner, including (1) capturing digital images having (i) square pixels (i.e. 1:1 aspect ratio) independent of package height or velocity, (ii) significantly reduced speckle-noise pattern levels, and (iii) constant image resolution measured in dots per inch (DPI) independent of package height or velocity and without the use of costly telecentric optics employed by prior art systems, (2) automatic cropping of captured images so that only regions of interest reflecting the package or package label are transmitted to the image processing computer (for 1-D or 2-D bar code symbol decoding or optical character recognition (OCR) image processing) , and (3) automatic image lifting operations for supporting other package management operations carried out by the end-user;

Fig. 27 is a schematic representation of the four-sided tunnel-type package identification and dimensioning (PID) system constructed by arranging about a high-speed package conveyor belt subsystem, one PLIIM-based PID unit (as shown in Fig. 9) and three modified PLIIM-based PID units (without the LDIP Subsystem), wherein the LDIP subsystem in the top PID unit is

configured as the master unit to detect and dimension packages transported along the belt, while the bottom PID unit is configured as a slave unit to view packages through a small gap between conveyor belt sections and the side PID units are configured as slave units to view packages from side angles slightly downstream from the master unit, and wherein all of the PID units are operably connected to an Ethernet control hub (e.g. contained within one of the slave units) of a local area network (LAN) providing high-speed data packet communication among each of the units within the tunnel system;

Fig. 28 is a schematic system diagram of the tunnel-type system shown in Fig. 27, embedded within a first-type LAN having an Ethernet control hub (e.g. contained within one of the slave units);

Fig. 29 is a schematic system diagram of the tunnel-type system shown in Fig. 27, embedded within a second-type LAN having a Ethernet control hub and a Ethernet data switch (e.g. contained within one of the slave units), and a fiber-optic (FO) based network, to which a keying-type computer work station is connected at a remote distance within a package counting facility;

Fig. 30 is a schematic representation of the camera-based package identification and dimensioning subsystem of Fig. 27, illustrating the system architecture of the slave units in relation to the master unit, and that (1) the package height, width, and length coordinates data and velocity data elements (computed by the LDIP subsystem within the master unit) are produced by the master unit and defined with respect to the global coordinate reference system, and (2) these package dimension data elements are transmitted to each slave unit on the data communication network, converted into the package height, width, and length coordinates, and used to generate real-time camera control signals which intelligently drive the camera subsystem within each slave unit, and (3) the package identification data elements generated by any one of the slave units are automatically transmitted to the master slave unit for time-stamping, queuing, and processing to ensure accurate package dimension and identification data element linking operations in accordance with the principles of the present invention;

Fig. 31 is a schematic representation of the tunnel-type system of Fig. 27, illustrating that package dimension data (i.e. height, width, and length coordinates) is (i) centrally computed by the master unit and referenced to a global coordinate reference frame, (ii) transmitted over the data network to each slave unit within the system, and (iii) converted to the local coordinate reference frame of each slave unit for use by its camera control computer to drive its automatic zoom and focus imaging optics in an intelligent, real-time manner in accordance with the principles of the present invention;

Figs. 32A and 32B, taken together, provide a high-level flow chart describing the primary steps involved in carrying out the novel method of controlling local vision-based camera subsystems deployed within a tunnel-based system, using real-time package dimension data centrally computed with respect to a global/central coordinate frame of reference, and distributed to local package identification units over a high-speed data communication network;

Fig. 33A is a schematic representation of a first illustrative embodiment of the bioptical PLIIM-based product dimensioning, analysis and identification system of the present invention, comprising a pair of PLIIM-based package identification and dimensioning subsystems, wherein each PLIIM-based subsystem employs visible laser diodes (VLDs) having different color producing wavelengths to produce a multi-spectral planar laser illumination beam (PLIB), and a 1-D (linear-type) CCD image detection array within the compact system housing to capture images of objects (e.g. produce) that are processed in order to determine the shape/geometry, dimensions and color of such products in diverse retail shopping environments;

Fig. 33B is a schematic representation of the bioptical PLIIM-based product dimensioning, analysis and identification system of Fig. 33A, showing its PLIIM-based subsystems and 2-D scanning volume in greater detail;

Fig. 33C is a system block diagram illustrating the system architecture of the bioptical PLIIM-based product dimensioning, analysis and identification system of the first illustrative embodiment shown in Figs. 33A and 33B;

Fig. 34A is a schematic representation of a second illustrative embodiment of the bioptical PLIIM-based product dimensioning, analysis and identification system of the present invention, comprising a pair of PLIIM-based package identification and dimensioning subsystems, wherein each PLIIM-based subsystem employs visible laser diodes (VLDs) having different color producing wavelengths to produce a multi-spectral planar laser illumination beam (PLIB), and a 2-D (area-type) CCD image detection array within the compact system housing to capture images of objects (e.g. produce) that are processed in order to determine the shape/geometry, dimensions and color of such products in diverse retail shopping environments;

Fig. 34B is a schematic representation of the bioptical PLIIM-based product dimensioning, analysis and identification system of Fig. 34A, showing its PLIIM-based subsystems and 3-D scanning volume in greater detail;

Fig. 34C is a system block diagram illustrating the system architecture of the bioptical PLIIM-based product dimensioning, analysis and identification system of the second illustrative embodiment shown in Figs. 34A and 34B;

Fig. 35A is a schematic perspective view of the planar laser illumination module (PLIM) realized on a semiconductor chip, wherein a micro-sized (diffractive or refractive) cylindrical lens array is mounted upon a large linear array of surface emitting lasers (SELs) fabricated on a semiconductor substrate, and encased within an integrated circuit package, so as to produce a planar laser illumination beam (PLIB) composed of numerous (e.g. 100-400) spatially incoherent laser beams emitted from said linear array of SELs in accordance with the principles of the present invention;

Fig. 35B is a perspective view of an illustrative embodiment of the PLIM semiconductor chip of the present invention, showing its semiconductor package provided with electrical connector pins and elongated light transmission window, through which a planar laser illumination beam is generated and transmitted in accordance with the principles of the present invention;

Fig. 36A is a cross-sectional schematic representation of PLIM-based semiconductor chip of the present invention, constructed from "45 degree mirror" surface emitting lasers (SELs);

Fig. 36B is a cross-sectional schematic representation of PLIM-based semiconductor chip of the present invention, constructed from "grating-coupled" SELs;

Fig. 36C is a cross-sectional schematic representation of PLIM-based semiconductor chip of the present invention, constructed from "vertical cavity" SELs, or VCSELs; and

Fig. 37 is a schematic perspective view of a planar laser illumination and imaging module (PLIIM) of the present invention realized on a semiconductor chip, wherein a pair of micro-sized (diffractive or refractive) cylindrical lens arrays are mounted upon a pair of large linear arrays of surface emitting lasers (SELs) (of corresponding length characteristics) fabricated on opposite sides of a linear CCD image detection array, and wherein both the linear CCD image detection array and linear SEL arrays are formed a common semiconductor substrate, encased within an integrated circuit (IC) package, and collectively produce a composite planar laser illumination beam (PLIB) that is transmitted through a pair of light transmission windows formed in the IC package and aligned substantially within the planar field of view (FOV) provided by the linear CCD image detection array in accordance with the principles of the present invention;

Fig. 38A is a schematic representation of a CCD/VLD PLIIM-based semiconductor chip of the present invention, wherein a plurality of electronically-activatable linear SEL arrays are used to electro-optically scan (i.e. illuminate) the entire 3-D FOV of CCD image detection array contained within the same integrated circuit package, without using mechanical scanning mechanisms; and

Fig. 38B is a schematic representation of the CCD/VLD PLIIM-based semiconductor chip of Fig. 38A, showing a 2D array of surface emitting lasers (SELs) formed about a 2D area-type CCD image detection array on a common semiconductor substrate, with a field of view defining lens element mounted over the 2D CCD image detection array and a 2D array of cylindrical lens elements mounted over the 2D array of SELs.

DETAILED DESCRIPTION OF THE ILLUSTRATIVE EMBODIMENTS OF THE PRESENT INVENTION

Referring to the figures in the accompanying Drawings, the preferred embodiments of the Planar Laser Illumination and (Electronic) Imaging (PLIIM) System of the present invention will be described in great detail, wherein like elements will be indicated using like reference numerals.

Overview of the Planar Laser Illumination And Electronic Imaging (PLIIM) System Of The Present Invention

In accordance with the principles of the present invention, an object (e.g. a bar coded package, textual materials, graphical indicia, etc.) is illuminated by a substantially planar laser illumination beam having substantially-planar spatial distribution characteristics along a planar direction which passes through the field of view (FOV) of an image formation and detection module (e.g. realized within a CCD-type digital electronic camera, a 35 mm optical-film photographic camera , or on a semiconductor chip as shown in Figs. 37 through 38B hereof), while images of the illuminated target object are formed and detected by the image formation and detection (i.e. camera) module.

This inventive principle of coplanar laser illumination and image formation is embodied in two different classes of the PLIIM, namely: (1) in PLIIM systems shown in Figs. 1A, 1V1, 2A, 2I1, 3A, and 3J1, wherein the image formation and detection modules in these systems employ linear-type (1-D) image detection arrays; and (2) in PLIIM systems shown in Figs. 4A, 5A and 6A, wherein the image formation and detection modules in these systems employ area-type (2-D) image detection arrays. Among these illustrative systems, those shown in Figs. 1A, 2A and 3A each produce a planar laser illumination beam that is neither scanned nor deflected relative to the system housing during planar laser illumination and image detection operations and thus can be said to use "stationary" planar laser illumination beams to read relatively moving bar code symbol structures and other graphical indicia. Those systems shown in Figs. 1V1, 2I1, 3J1, 4A, 5A and 6A, each produce a planar laser illumination beam that is scanned (i.e. deflected) relative to the system housing during planar laser illumination and image detection operations and thus can be said to use "moving" planar laser illumination beams to read relatively stationary bar code symbol structures and other graphical indicia.

In each such system embodiment, it is preferred that each planar laser illumination beam is focused so that the minimum beam width thereof (e.g. 0.6 mm along its non-spreading direction, as shown in Fig. 1I2) occurs at a point or plane which is the farthest or maximum working (i.e. object) distance at which the system is designed to acquire images of objects, as best shown in Fig. 1I2. Hereinafter, this aspect of the present invention shall be deemed the "Focus Beam At Farthest Object Distance (FBAFOD)" principle.

In the case where a fixed focal length imaging subsystem is employed in the PLIIM system, the FBAFOD principle helps compensate for decreases in the power density of the incident planar laser illumination beam due to the fact that the width of the planar laser illumination beam increases in length for increasing object distances away from the imaging subsystem.

In the case where a variable focal length (i.e. zoom) imaging subsystem is employed in the PLIIM system, the FBAFOD principle helps compensate for (i) decreases in the power density of the incident planar illumination beam due to the fact that the width of the planar laser illumination beam increases in length for increasing object distances away from the imaging subsystem, and (ii) any $1/r^2$ type losses that would typically occur when using the planar laser planar illumination beam of the present invention.

By virtue of the present invention, scanned objects need only be illuminated along a single plane which is coplanar with a planar section of the field of view of the image formation and detection module (e.g. camera) during illumination and imaging operations carried out by the PLIIM system. This enables the use of low-power, light-weight, high-response, ultra-compact, high-efficiency solid-state illumination producing devices, such as visible laser diodes (VLDs), to selectively illuminate ultra-narrow sections of an object during image formation and detection operations, in contrast with high-power, low-response, heavy-weight, bulky, low-efficiency lighting equipment (e.g. sodium vapor lights) required by prior art illumination and image detection systems. In addition, the planar laser illumination techniques of the present invention enables high-speed modulation of the planar laser illumination beam, and use of simple (i.e. substantially-monochromatic wavelength) lens designs for substantially-monochromatic optical illumination and image formation and detection operations.

As will be illustrated in greater detail hereinafter, PLIIM systems embodying the "planar laser illumination" and "FBAFOD" principles of the present invention can be embodied within a wide variety of bar code symbol reading and scanning systems, as well as optical character, text, and image recognition systems well known in the art.

In general, bar code symbol reading systems can be grouped into at least two general scanner categories, namely: industrial scanners; and point-of-sale (POS) scanners.

An industrial scanner is a scanner that has been designed for use in a warehouse or shipping application where large numbers of packages must be scanned in rapid succession. Industrial scanners include conveyor-type scanners, and hold-under scanners. These scanner categories will be described in greater detail below

Conveyor scanners are designed to scan packages as they move by on a conveyor belt. In general, a minimum of six conveyors (e.g. one overhead scanner, four side scanners, and one bottom scanner) are necessary to obtain complete coverage of the conveyor belt and ensure that any label will be scanned no matter where on a package it appears. Conveyor scanners can be further grouped into top, side, and bottom scanners which will be briefly summarized below.

Top scanners are mounted above the conveyor belt and look down at the tops of packages transported therealong. It might be desirable to angle the scanner's field of view slightly in the direction from which the packages approach or that in which they recede depending on the shapes of the packages being scanned. A top scanner generally has less severe depth of field and variable focus or dynamic focus requirements compared to a side scanner as the tops of packages are usually fairly flat, at least compared to the extreme angles that a side scanner might have to encounter during scanning operations.

Side scanners are mounted beside the conveyor belt and scan the sides of packages transported therealong. It might be desirable to angle the scanner's field of view slightly in the direction from which the packages approach or that in which they recede depending on the shapes of the packages being scanned and the range of angles at which the packages might be rotated.

Side scanners generally have more severe depth of field and variable focus or dynamic focus requirements compared to a top scanner because of the great range of angles at which the sides of the packages may be oriented with respect to the scanner (this assumes that the packages can have random rotational orientations; if an apparatus upstream on the on the conveyor forces the packages into consistent orientations, the difficulty of the side scanning task is lessened). Because side scanners can accommodate greater variation in object distance over the surface of a single target object, side scanners can be mounted in the usual position of a top scanner for applications in which package tops are severely angled.

Bottom scanners are mounted beneath the conveyor and scans the bottoms of packages by looking up through a break in the belt that is covered by glass to keep dirt off the scanner. Bottom scanners generally do not have to be variably or dynamically focused because its working distance is roughly constant, assuming that the packages are intended to be in contact with the conveyor belt under normal operating conditions. However, boxes tend to bounce around as they travel on the belt, and this behavior can be amplified when a package crosses the break, where one belt section ends and another begins after a gap of several inches. For this reason, bottom scanners must have a large depth of field to accommodate these random motions, to which a variable or dynamic focus system could not react quickly enough.

Hold-under scanners are designed to scan packages that are picked up and held underneath it. The package is then manually routed or otherwise handled, perhaps based on the result of the scanning operation. Hold-under scanners are generally mounted so that its viewing optics are oriented in downward direction, like a library bar code scanner. Depth of field (DOF) is an important characteristic for hold-under scanners, because the operator will not be able to hold the package perfectly still while the image is being acquired.

Point-of-sale (POS) scanners are typically designed to be used at a retail establishment to determine the price of an item being purchased. POS scanners are generally smaller than industrial scanner models, with more artistic and ergonomic case designs. Small size, low weight, resistance to damage from accident drops and user comfort are all major design factors for POS scanner. POS scanners include hand-held scanners, hands-free presentation scanners and combination-type scanners supporting both hands-on and hands-free modes of operation. These scanner categories will be described in greater detail below.

Hand-held scanners are designed to be picked up by the operator and aimed at the label to be scanned.

Hands-free presentation scanners are designed to remain stationary and have the item to be scanned picked up and passed in front of the scanning device. Presentation scanners can be mounted on counters looking horizontally, embedded flush with the counter looking vertically, or partially embedded in the counter looking vertically, but having a "tower" portion which rises out above the counter and looks horizontally to accomplish multiple-sided scanning. If necessary, presentation scanners that are mounted in a counter surface can also include a scale to measure weights of items.

Some POS scanners can be used as handheld units or mounted in stands to serve as presentation scanners, depending on which is more convenient for the operator based on the item that must be scanned.

Various generalized embodiments of the PLIIM system of the present invention will now be described in great detail, and after each generalized embodiment, various applications thereof will be described.

First Generalized Embodiment Of The PLIIM System Of The Present Invention

The first generalized embodiment of the PLIIM system of the present invention 1 is illustrated in Fig. 1A. As shown therein, the PLIIM system 1 comprises: a housing 2 of compact construction; a linear (i.e. 1-dimensional) type image formation and detection (IFD) 3 including a 1-D electronic image detection array 3A, and a linear (1-D) imaging subsystem (LIS) 3B having a fixed focal length, a fixed focal distance, and a fixed field of view (FOV), for forming a 1-D image of an illuminated object 4 located within the fixed focal distance and FOV thereof and projected onto the 1-D image detection array 3A, so that the 1-D image detection array 3A can electronically detect the image formed thereon and automatically produce a digital image data set 5 representative of the detected image for subsequent image processing; and a pair of planar laser illumination arrays (PLIAs) 6A and 6B , each mounted on opposite sides of the IFD module 3, such that each planar laser illumination array 6A and 6B produces a plane of laser beam illumination 7A, 7B which is disposed substantially coplanar with the field view of the image formation and detection module 3 during object illumination and image detection operations carried out by the PLIIM system.

An image formation and detection (IFD) module 3 having an imaging lens with a fixed focal length has a constant angular field of view (FOV); that is, the imaging subsystem can view more of the target object's surface as the target object is moved further away from the IFD module. A major disadvantage to this type of imaging lens is that the resolution of the image that is acquired, expressed in terms of pixels or dots per inch (dpi), varies as a function of the distance from the target object to the imaging lens. However, a fixed focal length imaging lens is easier and less expensive to design and produce than a zoom-type imaging lens which will be discussed in detail hereinbelow with reference to Figs. 3A through 3J4.

The distance from the imaging lens 3B to the image detecting (i.e. sensing) array 3A is referred to as the image distance. The distance from the target object 4 to the imaging lens 3B is called the object distance. The relationship between the object distance (where the object resides) and the image distance (at which the image detection array is mounted) is a function of the characteristics of the imaging lens, and assuming a thin lens, is determined by the thin (imaging) lens equation (1) defined below in greater detail. Depending on the image distance, light reflected from a target object at the object distance will be brought into sharp focus on the detection array plane. If the image distance remains constant and the target object is moved to a new object distance, the imaging lens might not be able to bring the light reflected off the target

object (at this new distance) into sharp focus. An image formation and detection (IFD) module having an imaging lens with fixed focal distance cannot adjust its image distance to compensate for a change in the target's object distance; all the component lens elements in the imaging subsystem remain stationary. Therefore, the depth of field (DOF) of the imaging subsystems alone must be sufficient to accommodate all possible object distances and orientations. Such basic optical terms and concepts will be discussed in more formal detail hereinafter with reference to Figs. 1J1 and 1J6.

In accordance with the present invention, the planar laser illumination arrays 6A and 6B , the linear image formation and detection module 3 , and any non-moving FOV and/or planar laser illumination beam folding mirrors employed in any particular system configuration described herein, are fixedly mounted on an optical bench 8 or chassis so as to prevent any relative motion (which might be caused by vibration or temperature changes) between: (i) the image forming optics (e.g. imaging lens) within the image formation and detection module 3 and any stationary FOV folding mirrors employed therewith; and (ii) each planar laser illumination array (i.e. VLD/cylindrical lens assembly) 6A, 6B and any planar laser illumination beam folding mirrors employed in the PLIIM system configuration. Preferably, the chassis assembly should provide for easy and secure alignment of all optical components employed in the planar laser illumination arrays 6A and 6B as well as the image formation and detection module 3, as well as be easy to manufacture, service and repair. Also, this PLIIM system 1 employs the general "planar laser illumination" and "focus beam at farthest object distance (FBAFOD)" principles described above. Various illustrative embodiments of this generalized PLIIM system will be described below.

<u>First Illustrative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 1A</u>

The first illustrative embodiment of the PLIIM system 1A of Fig. 1A is shown in Fig. 1B1. As illustrated therein, the field of view of the image formation and detection module 3 is folded in the downwardly direction by a field of view (FOV) folding mirror 9 so that both the folded field of view 10 and resulting first and second planar laser illumination beams 7A and 7B produced by the planar illumination arrays 6A and 6B, respectively, are arranged in a substantially coplanar relationship during object illumination and image detection operations. One primary advantage of this system design is that it enables a construction having an ultra-low height profile suitable, for example, in unitary package identification and dimensioning systems of the type disclosed in Figs. 17-22, wherein the image-based bar code symbol reader needs to installed within a compartment (or cavity) of a housing having relatively low height dimensions. Also, in this system design, there is a relatively high degree of freedom provided in where the image formation and detection module 3 can be mounted on the optical bench of the system, thus enabling the field of view (FOV) folding technique disclosed in Fig. 1L1 to practiced in a relatively easy manner.

The PLIIM system 1A illustrated in Fig. 1B1 is shown in greater detail in Fig. 1B2. As shown therein, the linear image formation and detection module 3 is shown comprising an imaging subsystem 3B, and a linear array of photo-electronic detectors 3A realized using high-speed CCD technology (e.g. Dalsa IT-P4 Linear Image Sensors, from Dalsa, Inc. located on the WWW at http://www.dalsa.com). As shown, each planar laser illumination array 6A, 6B comprises a plurality of planar laser illumination modules (PLIMs) 11A through 11F, closely arranged relative to each other, in a rectilinear fashion. For purposes of clarity, each PLIM is indicated by reference numeral. As shown in Figs. 1K1 and 1K2, the relative spacing of each PLIM is such that the spatial intensity distribution of the individual planar laser beams superimpose and additively provide a substantially uniform composite spatial intensity distribution for the entire planar laser illumination array 6A and 6B.

Fig. 1C is a schematic representation of a single planar laser illumination module (PLIM) 11 used to construct each planar laser illumination array 6A, 6B shown in Fig. 1B2. As shown in Fig. 1C, the planar laser illumination beam emanates substantially within a single plane along the direction of beam propagation towards an object to be optically illuminated.

As shown in Fig. 1D, the planar laser illumination module of Fig. 1C, comprises: a visible laser diode (VLD) 13 supported within an optical tube or block 14; a light collimating lens 15 supported within the optical tube 14; and a cylindrical-type lens element 16 configured together to produce a beam of planar laser illumination 12. As shown in Fig. 1E, a focused laser beam 17 from the focusing lens 15 is directed on the input side of the cylindrical lens element 16, and the produced output therefrom is a planar laser illumination beam 12.

As shown in Fig. 1F, the PLIIM system 1A of Fig. 1A comprises: planar laser illumination arrays 6A and 6B, each having a plurality of PLMS 11A through 11F, and each PLIM being driven by a VLD driver circuit 18 well known in the art; linear-type image formation and detection module 3; field of view (FOV) folding mirror 9, arranged in spatial relation with the image formation and detection module 3; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer, including image-based bar code symbol decoding software such as, for example, SwiftDecode™ Bar Code Decode Software, from Omniplanar, Inc., of Princeton, New Jersey (http://www.omniplanar.com); and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Detailed Description Of An Exemplary Realization Of The PLIIM System Shown In Fig. 1B1 Through 1F

Referring now to Figs. 1G1 through 1N2, an exemplary realization of the PLIIM system shown in Figs. 1B1 through 1F will now be described in detail below.

As shown in Figs. 1G1 and 1G2, the PLIIM system 25 of the illustrative embodiment is contained within a compact housing 26 having height, length and width dimensions 45", 21.7", and 19.7" to enable easy mounting above a conveyor belt structure or the like. As shown in Fig. 1G1, the PLIIM system comprises an image formation and detection module 3, a pair of planar laser illumination arrays 6A, 6B, and a stationary field of view (FOV) folding structure (e.g. mirror, refractive element, or diffractive element) 9, as shown in Figs. 1B1 and 1B2. The function of the FOV folding mirror 9 is to fold the field of view (FOV) of the image formation and detection module 3 in a direction that is coplanar with the plane of laser illumination beams 7A and 7B produced by the planar illumination arrays 6A and 6B respectively. As shown, components 6A, 6B, 3 and 9 are fixedly mounted to an optical bench 8 supported within the compact housing 26 by way of metal mounting brackets that force the assembled optical components to vibrate together on the optical bench. In turn, the optical bench is shock mounted to the system housing using techniques which absorb and dampen shock forces and vibration. The 1-D CCD imaging array 3A can be realized using a variety of commercially available high-speed line-scan camera systems such as, for example, the Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com. Notably, image frame grabber 17, image data buffer (e.g. VRAM) 20, image processing computer 21, and camera control computer 22 are realized on one or more printed circuit (PC) boards contained within a camera and system electronic module 27 also mounted on the optical bench, or elsewhere in the system housing 26

In general, the linear CCD image detection array (i.e. sensor) 3A has a single row of pixels, each of which measures from several μm to several tens of μm along each dimension. Square pixels are most common, and most convenient for bar code scanning applications, but different aspect ratios are available. In principle, a linear CCD detection array can see only a small slice of the target object it is imaging at any given time. For example, for a linear CCD detection array having 2000 pixels, each of which is 10μm square, the detection array measures 2 cm long by 10μm high. If the imaging lens 3B in front of the linear detection array 3A causes an optical magnification of 10X, then the 2 cm length of the detection array will be projected onto a 20 cm length of the target object. In the other dimension, the 10μm height of the detection array becomes only 100μm when projected onto the target. Since any label to be scanned will typically measure more than a hundred μm or so in each direction, capturing a single image with a linear image detection array will be inadequate. Therefore, in practice, the linear image detection array employed in each of the PLIIM systems shown in Figs. 1A through 3J6 builds up a complete image of the target object by assembling a series of linear (1-D) images, each of which is taken of a different slice of the target object. Therefore, successful use of a linear image detection array in the PLIIM systems shown in Figs. 1A through 3J6 requires relative movement between the target object and the PLIIM system. In general, either the target object is moving

and the PLIIM system is stationary, or else the field of view of PLIIM system is swept across a relatively stationary target object, as shown in Figs. 3J1 through 3J4. This makes the linear image detection array a natural choice for conveyor scanning applications.

As shown in Fig. 1G1, the compact housing 26 has a relatively long light transmission window 28 of elongated dimensions for projecting the FOV of the image formation and detection module 3 through the housing towards a predefined region of space outside thereof, within which objects can be illuminated and imaged by the system components on the optical bench 8. Also, the compact housing 26 has a pair of relatively short light transmission apertures 29A and 29B closely disposed on opposite ends of light transmission window 28, with minimal spacing therebetween, as shown in Fig. 1G1, so that the FOV emerging from the housing 26 can spatially overlap in a coplanar manner with the substantially planar laser illumination beams projected through transmission windows 29A and 29B, as close to transmission window 28 as desired by the system designer, as shown in Figs. 1G3 and 1G4. Notably, in some applications, it is desired for such coplanar overlap between the FOV and planar laser illumination beams to occur very close to the light transmission windows 20, 29A and 29B (i.e. at short optical throw distances), but in other applications, for such coplanar overlap to occur at large optical throw distances.

In either event, each planar laser illumination array 6A and 6B is optically isolated from the FOV of the image formation and detection module 3. In the preferred embodiment, such optical isolation is achieved by providing a set of opaque wall structures 30A 30B about each planar laser illumination array, from the optical bench 8 to its light transmission window 29A or 29B, respectively. Such optical isolation structures prevent the image formation and detection module 3 from detecting any laser light transmitted directly from the planar laser illumination arrays 6A, 6B within the interior of the housing. Instead, the image formation and detection module 3 can only receive planar laser illumination that has been reflected off an illuminated object, and focused through the imaging subsystem of module 3.

As shown in Fig. 1G3, each planar laser illumination array 6A, 6B comprises a plurality of planar laser illumination modules 11A through 11F, each individually and adjustably mounted to an L-shaped bracket 32 which, in turn, is adjustably mounted to the optical bench. As mentioned above, each planar laser illumination module 11 must be rotatably adjustable within its L-shaped bracket so as permit easy yet secure adjustment of the position of each PLIM 11 along a common alignment plane extending within L-bracket portion 32A thereby permitting precise positioning of each PLIM relative to the optical axis of the image formation and detection module 3. Once properly adjusted in terms of position on the L-bracket portion 32A, each PLIM can be securely locked by an allen or like screw threaded into the body of the L-bracket portion 32A. Also, L-bracket portion 32B, supporting a plurality of PLIMS 11A through 11B, is adjustably mounted to the optical bench 8 and releasably locked thereto so as to permit precise lateral and/or angular positioning of the L-bracket 32B relative to the optical axis and FOV of the image formation and detection module 3. The function of such adjustment mechanisms is to enable the intensity distributions of the individual PLIMs to be additively configured together along a substantially singular plane, typically having a width or thickness

dimension on the orders of the width and thickness of the spread or dispersed laser beam within each PLIM. When properly adjusted, the composite planar laser illumination beam will exhibit substantially uniform power density characteristics over the entire working range of the PLIIM system, as shown in Figs. 1K1 and 1K2.

In Fig. 1G3, the exact position of the individual PLIMs 11A through 11Falong its L-bracket 32A is indicated relative to the optical axis of the imaging lens 3B within the image formation and detection module 3. Fig. 1G3 also illustrates the geometrical limits of each substantially planar laser illumination beam produced by its corresponding PLIM, measured relative to the folded FOV 10 produced by the image formation and detection module 3. Fig. 1G4, illustrates how, during object illumination and image detection operations, the FOV of the image formation and detection module 3 is first folded by FOV folding mirror 19, and then arranged in a spatially overlapping relationship with the resulting/composite planar laser illumination beams in a coplanar manner in accordance with the principles of the present invention.

Notably, the PLIIM system of Fig. 1G1 has an image formation and detection module with an imaging subsystem having a fixed focal distance lens and a fixed focusing mechanism. Thus, such a system is best used in either hand-held scanning applications, and/or bottom scanning applications where bar code symbols and other structures can be expected to appear at a particular distance from the imaging subsystem. In Fig. 1G5, the spatial limits for the FOV of the image formation and detection module are shown for two different scanning conditions, namely: when imaging the tallest package moving on a conveyor belt structure; and when imaging objects having height values close to the surface of the conveyor belt structure. In a PLIIM system having a fixed focal distance lens and a fixed focusing mechanism, the PLIIM system would be capable of imaging objects under one of the two conditions indicated above, but not under both conditions. In a PLIIM system having a fixed focal length lens and a variable focusing mechanism, the system can adjust to image objects under either of these two conditions.

In order that PLLIM-based subsystem 25 can be readily interfaced to and an integrated (e.g. embedded) within various types of computer-based systems, as shown in Figs. 9 through 34C, subsystem 25 also comprises an I/0 subsystem 500 operably connected to camera control computer 22 and image processing computer 21, and a network controller 501 for enabling high-speed data communication with others computers in a local or wide area network using packet-based networking protocols (e.g. Ethernet, AppleTalk, etc.) well known in the art.

In the PLIIM system of Fig. 1G1, special measures are undertaken to ensure that (i) a minimum safe distance is maintained between the VLDs in each PLIM and the user's eyes, and (ii) the planar laser illumination beam is prevented from directly scattering into the FOV of the image formation and detection module, from within the system housing, during object illumination and imaging operations. Condition (i) above can be achieved by using a light shield 32A or 32B shown in Figs. 1G6 and 1G7, respectively, whereas condition (ii) above can be achieved by ensuring that the planar laser illumination beam from the PLIAs and the field of view (FOV) of the imaging lens (in the IFD module) do not spatially overlap on any optical

surfaces residing within the PLIIM system. Instead, the planar laser illumination beams are permitted to spatially overlap with the FOV of the imaging lens only outside of the system housing, measured at a particular point beyond the light transmission window 28, through which the FOV 10 is projected to the exterior of the system housing, to perform object imaging operations.

<u>Detailed Description Of The Planar Laser Illumination Modules (PLIMs) Employed In The Planar Laser Illumination Arrays (PLIAs) Of The Illustrative Embodiments</u>

Referring now to Figs. 1G8 through 1I2, the construction of each PLIM 14 and 15 used in the planar laser illumination arrays (PLIAs) will now be described in greater detail below.

As shown in Fig. 1G8, each planar laser illumination array (PLIA) 6A, 6Bemployed in the PLIIM system of Fig. 1G1, comprises an array of planar laser illumination modules (PLIMs) 11 mounted on the L-bracket structure 32, as described hereinabove. As shown in Figs. 1G9 through 1G11, each PLIM of the illustrative embodiment disclosed herein comprises an assembly of subcomponents: a VLD mounting block 14 having a tubular geometry with a hollow central bore 14A formed entirely therethrough, and a v-shaped notch 14B formed on one end thereof; a visible laser diode (VLD) 13 (e.g. Mitsubishi ML1XX6 Series high-power 658nm AlGaInP semiconductor laser) axially mounted at the end of the VLD mounting block, opposite the v-shaped notch 14B, so that the laser beam produced from the VLD 13 is aligned substantially along the central axis of the central bore 14A; a cylindrical lens 16, made of optical glass (e.g. borosilicate) or plastic having the optical characteristics specified, for example, in Figs. 1G1 and 1G2, and fixedly mounted within the V-shaped notch 14B at the end of the VLD mounting block 14, using an optical cement or other lens fastening means, so that the central axis of the cylindrical lens 16 is oriented substantially perpendicular to the optical axis of the central bore 14A; and a focusing lens 15, made of central glass (e.g. borosilicate) or plastic having the optical characteristics shown, for example, in Figs. IH and 1H2, mounted within the central bore 14A of the VLD mounting block 14 so that the optical axis of the focusing lens 15 is substantially aligned with the central axis of the bore 14A, and located at a distance from the VLD which causes the laser beam output from the VLD 13 to be converging in the direction of the cylindrical lens 16. Notably, the function of the cylindrical lens 16 is to disperse (i.e. spread) the focused laser beam from focusing lens 15 along the plane in which the cylindrical lens 16 has curvature, as shown in Fig. 1I1while the characteristics of the planar laser illumination beam (PLIB) in the direction transverse to the propagation plane are determined by the focal length of the focusing lens 15, as illustrated in Figs. 1I1 and 1I2.

As will be described in greater detail hereinafter, the focal length of the focusing lens 15within each PLIM hereof is preferably selected so that the substantially planar laser illumination beam produced from the cylindrical lens 16 is focused at the farthest object distance in the field of view of the image formation and detection module 3, as shown in Fig. 1I2, in accordance with the "FBAFOD" principle of the present invention. As shown in the exemplary

embodiment of Figs. 1I1 and 1I2, wherein each PLIM has maximum object distance of about 61 inches (i.e. 155 centimeters), and the cross-sectional dimension of the planar laser illumination beam emerging from the cylindrical lens 16, in the non-spreading (height) direction, oriented normal to the propagation plane as defined above, is about 0.15 centimeters and ultimately focused down to about 0.06 centimeters at the maximal object distance (i.e. the farthest distance at which the system is designed to capture images). The behavior of the height dimension of the planar laser illumination beam is determined by the focal length of the focusing lens 15 embodied within the PLIM. Proper selection of the focal length of the focusing lens 15 in each PLIM and the distance between the VLD 13 and the focusing lens 15B indicated by reference No. (D), can be determined using the thin lens equation (1) below and the maximum object distance required by the PLIIM system, typically specified by the end-user. As will be explained in greater detail hereinbelow, this preferred method of VLD focusing helps compensate for decreases in the power density of the incident planar laser illumination beam (on target objects) due to the fact that the width of the planar laser illumination beam increases in length for increasing distances away from the imaging subsystem (i.e. object distances).

After specifying the optical components for each PLIM, and completing the assembly thereof as described above, each PLIM is adjustably mounted to the L bracket position 32A by way of a set of mounting/adjustment screws turned through fine-threaded mounting holes formed thereon. In Fig. 1G10, the plurality of PLIMs 11A through 11F are shown adjustably mounted on the L-bracket at positions and angular orientations which ensure substantially uniform power density characteristics in both the near and far field portions of the planar laser illumination field produced by planar laser illumination arrays (PLIAs) 6A and 6B cooperating together in accordance with the principles of the present invention. Notably, the relative positions of the PLIMs indicated in Fig. 1G9 were determined for a particular set of a commercial VLDs 13 used in the illustrative embodiment of the present invention, and, as the output beam characteristics will vary for each commercial VLD used in constructing each such PLIM, it is therefore understood that each such PLIM may need to be mounted at different relative positions on the L-bracket of the planar laser illumination array to obtain, from the resulting system, substantially uniform power density characteristics at both near and far regions of the planar laser illumination field produced thereby.

While a refractive-type cylindrical lens element 16 has been shown mounted at the end of each PLIM of the illustrative embodiments, it is understood each cylindrical lens element can be realized using refractive, reflective and/or diffractive technology and devices, including reflection and transmission type holographic optical elements (HOEs) well know in the art and described in detail in International Application No. WO 99/57579 published on November 11, 1999, incorporated herein by reference. The only requirement of the optical element mounted at the end of each PLIM is that it has sufficient optical properties to convert a focusing laser beam transmitted therethrough, into a laser beam which expands or otherwise spreads out only along a single plane of propagation, while the laser beam is substantially unaltered (i.e. neither compressed or expanded) in the direction normal to the propagation plane. As used hereinafter

and in the claims, the terms "cylindrical lens", "cylindrical lens element" and "cylindrical optical element (COE)" shall be deemed to embrace all such alternative embodiments of this aspect of the present invention.

Detailed Description Of The Image Formation And Detection Module Employed In The PLIIM System Of The First Generalized Embodiment Of The Present Invention

In Fig. 1J1, there is shown a geometrical model (based on the thin lens equation) for the simple imaging subsystem 3B employed in the image formation and detection module 3 in the PLIIM system of the first generalized embodiment shown in Fig. 1A. As shown in Fig. 11J1, this simple imaging system 3B consists of a source of illumination (e.g. laser light reflected off a target object) and an imaging lens. The illumination source is at an object distance r_0 measured from the center of the imaging lens. In Fig. 1J1, some representative rays of light have been traced from the source to the front lens surface. The imaging lens is considered to be of the converging type which, for ordinary operating conditions, focuses the incident rays from the illumination source to form an image which is located at an image distance r_i on the opposite side of the imaging lens. In Fig. 1J1, some representative rays have also been traced from the back lens surface to the image. The imaging lens itself is characterized by a focal length f, the definition of which will be discussed in greater detail hereinbelow.

For the purpose of simplifying the mathematical analysis, the imaging lens is considered to be a thin lens, that is, idealized to a single surface with no thickness. The parameters f, r_0 and r_i, all of which have units of length, are related by the "thin lens" equation (1) set forth below:

$$\frac{1}{f}=\frac{1}{r_0}+\frac{1}{r_i} \qquad (1)$$

This equation may be solved for the image distance, which yields expression (2)

$$r_i=\frac{fr_0}{r_0-f} \qquad (2)$$

If the object distance r_0 goes to infinity, then expression (2) reduces to $r_i = f$. length of the imaging lens is the image distance at which light incident on the lens from an infinitely distant object will be focused. Once f is known, the image distance for light from any other object distance can be determined using (2).

Field of View of The Imaging Lens and Resolution of The Detected Image

The basic characteristics of an image detected by the IFD module 3 hereof may be determined using the technique of ray tracing, in which representative rays of light are drawn from the source through the imaging lens and to the image. Such ray tracing is shown in Fig. 1J2. A basic rule of ray tracing is that a ray from the illumination source that passes through the center of the imaging lens continues undeviated to the image. That is, a ray that passes through the center of the imaging lens is not refracted. Thus, the size of the field of view (FOV) of the imaging lens may be determined by tracing rays (backwards) from the edges of the image detection/sensing array through the center of the imaging lens and out to the image plane as shown in Fig. 1J2, where d is the dimension of a pixel, n is the number of pixels on the image detector array in this direction, and W is the dimension of the field of view of the imaging lens. Solving for the FOV dimension W, and substituting for r_i using expression (2) above yields expression (3) as follows:

$$W = \frac{dn(r_0 - f)}{f} \qquad (3)$$

Now that the size of the field of view is known, the dpi resolution of the image is determined. The dpi resolution of the image is simply the number of pixels divided by the dimension of the field of view. Assuming that all the dimensions of the system are measured in meters, the dots per inch (dpi) resolution of the image is given by the expression (4) as follows:

$$dpi = \frac{f}{39.37d(r_0 - f)} \qquad (4)$$

<u>Working Distance and Depth of Field of the Imaging Lens</u>

Light returning to the imaging lens that emanates from object surfaces slightly closer to and farther from the imaging lens than object distance r_0 will also appear to be in good focus on the image. From a practical standpoint, "good focus" is decided by the decoding software 21 used when the image is too blurry to allow the code to be read (i.e. decoded), then the imaging subsystem is said to be "out of focus". If the object distance r_0 at which the imaging subsystem is ideally focused is known, then it can be calculated theoretically the closest and farthest "working distances" of the PLIIM system, given by parameters r_{near} and r_{far}, respectively, at which the system will still function. These distance parameters are given by expression (5) and (6) as follows:

$$r_{near} = \frac{fr_0(f + DF)}{f^2 + DFr_0} \quad (5)$$

$$r_{far} = \frac{fr_0(f - DF)}{f^2 - DFr_0} \quad (6)$$

where D is the diameter of the largest permissible "circle of confusion" on the image detection array. A circle of confusion is essentially the blurred out light that arrives from points at image distances other than object distance r_0. When the circle of confusion becomes too large (when the blurred light spreads out too much) then one will lose focus. The value of parameter D for a given imaging subsystem is usually estimated from experience during system design, and then determined more precisely, if necessary, later through laboratory experiment.

Another optical parameter of interest is the total depth of field Δr, which is the difference between distances r_{far} and r_{near}; this parameter is the total distance over which the imaging system will be able to operate when focused at object distance r_0. This optical parameter may be expressed by equation (7) below:

$$\Delta r = \frac{2Df^2Fr_0(r_0 - f)}{f^4 - D^2F^2r_0^2} \quad (7)$$

It should be noted that the parameter Δr is generally not symmetric about r_0; the depth of field usually extends farther towards infinity from the ideal focal distance than it does back towards the imaging lens.

Modeling A Fixed Focal Length Imaging Subsystem Used In The Image Formation And Detection Module Of The Present Invention

A typical imaging (i.e. camera) lens used to construct a fixed focal-length image formation and detection module of the present invention might typically consist of three to fifteen or more individual optical elements contained within a common barrel structure. The inherent complexity of such an optical module prevents its performance from being described very accurately using a "thin lens analysis", described above by equation (1). However, the results of a thin lens analysis can be used as a useful guide when choosing an imaging lens for a particular PLIIM system application.

A typical imaging lens can focus light (illumination) originating anywhere from an infinite distance away, to a few feet away. However, regardless of the origin of such illumination, its

rays must be brought to a sharp focus at exactly the same location (e.g. the film plane or image detector), which (in an ordinary camera) does not move. At first glance, this requirement may appear unusual because the thin lens equation (1) above states that the image distance at which light is focused through a thin lens is a function of the object distance at which the light originates, as shown in Fig. 1J3. Thus, it would appear that the position of the image detector would depend on the distance at which the object being imaged is located. An imaging subsystem having a variable focal distance lens assembly avoids this difficulty because several of its lens elements are capable of movement relative to the others. For a fixed focal length imaging lens, the leading lens element(s) can move back and forth a short distance, usually accomplished by the rotation of a helical barrel element which converts rotational motion into purely linear motion of the lens elements. This motion has the effect of changing the image distance to compensate for a change in object distance, allowing the image detector to remain in place, as shown in the schematic optical diagram of Fig. 1J4.

Modeling A Variable Focal Length (Zoom) Imaging Lens Used In The Image Formation And Detection Module Of The Present Invention

As shown in Fig. 1J5, a variable focal length (zoom) imaging subsystem has an additional level of internal complexity. A zoom-type imaging subsystem is capable of changing its focal length over a given range; a longer focal length produces a smaller field of view at a given object distance. Consider the case where the PLIIM system needs to illuminate and image a certain object over a range of object distances, but requires the illuminated object to appear the same size in all acquired images. When the object is far away, the PLIIM system will generate control signals that select a long focal length, causing the field of view to shrink (to compensate for the decrease in apparent size of the object due to distance). When the object is close, the PLIIM system will generate control signals that select a shorter focal length, which widens the field of view and preserves the relative size of the object. In many bar code scanning applications, a zoom-type imaging subsystem in the PLIIM system (as shown in Figs. 3A through 3J5) ensures that all acquired images of bar code symbols have the same dpi image resolution regardless of the position of the bar code symbol within the object distance of the PLIIM system.

As shown in Fig. 1J5, a zoom-type imaging subsystem has two groups of lens elements which are able to undergo relative motion. The leading lens elements are moved to achieve focus in the same way as for a fixed focal length lens. Also, there is a group of lenses in the middle of the barrel which move back and forth to achieve the zoom, that is, to change the effective focal length of all the lens elements acting together.

Several Techniques For Accommodating The Field of View (FOV) Of A PLIIM System To Particular End-User Environments

In many applications, a PLIIM system of the present invention may include an imaging subsystem with a very long focal length imaging lens (assembly), and this PLIIM system must be installed in end-user environments having a substantially shorter object distance range, and/or field of view (FOV) requirements or the like. Such problems can exist for PLIIM systems employing either fixed or variable focal length imaging subsystems. To accommodate a particular PLIIM system for installation in such environments, three different techniques illustrated in Figs. 1K1-1K2, 1L1 and 1L2 can be used.

In Figs. 1K1 and 1K2, the focal length of the imaging lens 3B can be fixed and set at the factory to produce a field of view having specified geometrical characteristics for particular applications. In Fig. K1, the focal length of the image formation and detection module 3 is fixed during the optical design stage so that the fixed field of view (FOV) thereof substantially matches the scan field width measured at the top of the scan field, and thereafter overshoots the scan field and extends on down to the plane of the conveyor belt 34. In this FOV arrangement, the dpi image resolution will be greater for packages having a higher height profile above the conveyor belt, and less for envelope-type packages with low height profiles. In Fig. 1K2, the focal length of the image formation and detection module 3 is fixed during the optical design stage so that the fixed field of view thereof substantially matches the plane slightly above the conveyor belt 34 where envelope-type packages are transported. In this FOV arrangement, the dpi image resolution will be maximized for envelope-type packages which are expected to be transported along the conveyor belt structure, and this system will be unable to read bar codes on packages having a height-profile exceeding the low-profile scanning field of the system.

In Fig. 1L, a FOV beam folding mirror arrangement is used to fold the optical path of the imaging subsystem within the interior of the system housing so that the FOV emerging from the system housing has geometrical characteristics that match the scanning application at hand. As shown, this technique involves mounting a plurality of FOV folding mirrors 9A through 9E on the optical bench of the PLIIM system to bounce the FOV of the imaging subsystem 3B back and forth before the FOV emerges from the system housing. Using this technique, when the FOV emerges from the system housing, it will have expanded to a size appropriate for covering the entire scan field of the system. This technique is easier to practice with image formation and detection modules having linear image detectors, for which the FOV folding mirrors only have to expand in one direction as the distance from the imaging subsystem increases. In Fig. 1L, this direction of FOV expansion occurs in the direction perpendicular to the page. In the case of area-type PLIIM systems, as shown in Figs. 4A through 6F4, the FOV folding mirrors have to accommodate a 3-D FOV which expands in two directions. Thus an internal folding path is easier to arrange for linear-type PLIIM systems.

In Fig. 1L2, the fixed field of view of an imaging subsystem is expanded across a working space (e.g. conveyor belt structure) by using a motor 35 to controllably rotate the FOV 10 during object illumination and imaging operations. When designing a linear-type PLIIM system for industrial scanning applications, wherein the focal length of the imaging subsystem is fixed, a higher dpi image resolution will occasionally be required. This implies using a longer

focal length imaging lens, which produces a narrower FOV and thus higher dpi image resolution. However, in many applications, the image formation and detection module in the PLIIM system cannot be physically located far enough away from the conveyor belt (and within the system housing) to enable the narrow FOV to cover the entire scanning field of the system. In this case, a FOV folding mirror 9F can be made to rotate, relative to stationary for folding mirror 9G, in order to sweep the linear FOV from side to side over the entire width of the conveyor belt, depending on where the bar coded package is located. Ideally, this rotating FOV folding mirror 9F would have only two mirror positions, but this will depend on how small the FOV is at the top of the scan field. The rotating FOV folding mirror can be driven by motor 35 operated under the control of the camera control computer 22, as described herein.

<u>Method of Adjusting the Focal Characteristics of the Planar Laser Illumination Beams Generated by Planar Laser Illumination Arrays Used in Conjunction with Image Formation And Detection Modules Employing Fixed Focal Length Imaging Lenses</u>

In the case of a fixed focal length camera lens, the planar laser illumination beam 7A, 7B is focused at the farthest possible object distance in the PLIIM system. In the case of fixed focal length imaging lens, this focus control technique of the present invention is not employed to compensate for decrease in the power density of the reflected laser beam as a function of $1/r^2$ distance from the imaging subsystem, but rather to compensate for a decrease in power density of the planar laser illumination beam on the target object due to an increase in object distance away from the imaging subsystem.

It can be shown that laser return light that is reflected by the target object (and measured/detected at any arbitrary point in space) decreases in intensity as the inverse square of the object distance. In the PLIIM system of the present invention, the relevant decrease in intensity is not related to such "inverse square" law decreases, but rather to the fact that the width of the planar laser illumination beam increases as the object distance increases. This "beam-width/object-distance" law decrease in light intensity will be described in greater detail below.

Using a thin lens analysis of the imaging subsystem, it can be shown that when any form of illumination having a uniform power density E_0 (i.e. power per unit area) is directed incident on a target object surface and the reflected laser illumination from the illuminated object is imaged through an imaging lens having a fixed focal length f and f-stop F, the power density E_{pix} (measured at the pixel of the image detection array and expressed as a function of the object distance r) is provided by the expression (8) set forth below:

$$E_{pix} = \frac{E_0}{8F}(1-\frac{f}{r})^2 \qquad (8)$$

Fig. 1M1 shows a plot of pixel power density E_{pix} vs. object distance r calculated using the arbitrary but reasonable values $E_0 = 1$ W/m^2, f = 80 mm and F = 4.5. This plot demonstrates

that, in a counter-intuitive manner, the power density at the pixel (and therefore the power incident on the pixel, as its area remains constant) actually increases as the object distance increases. Careful analysis explains this particular optical phenomenon by the fact that the field of view of each pixel on the image detection array increases slightly faster with increases in object distances than would be necessary to compensate for the $1/r^2$ return light losses. A more analytical explanation is provided below.

The width of the planar laser illumination beam increases as object distance r increases. At increasing object distances, the constant output power from the VLD in each planar laser illumination module (PLIM) is spread out over a longer beam width, and therefore the power density at any point along the laser beam width decreases. To compensate for this phenomenon, the planar laser illumination beam of the present invention is focused at the farthest object distance so that the height of the planar laser illumination beam becomes smaller as the object distance increases; as the height of the planar laser illumination beam becomes narrower towards the farthest object distance, the laser beam power density increases at any point along the width of the planar laser illumination beam. The decrease in laser beam power density due to an increase in planar laser beam width and the increase in power density due to a decrease in planar laser beam height, roughly cancel each other out, resulting in a power density which either remains approximately constant or increases as a function of increasing object distance, as the application at hand may require.

When the laser beam is fanned (i.e. spread) out into a substantially planar laser illumination beam by the cylindrical lens element employed within each PLIM in the PLIIM system, the total output power in the planar laser illumination beam is distributed along the width of the beam in a roughly Gaussian distribution, as shown in the power vs. position plot of Fig. 1M2. Notably, this plot was constructed using actual data gathered with a planar laser illumination beam focused at the farthest object distance in the PLIIM system. For comparison purposes, the data points and a Gaussian curve fit are shown for the planar laser beam widths taken at the nearest and farthest object distances. To avoid having to consider two dimensions simultaneously (i.e. left-to-right along the planar laser beam width dimension and near-to-far through the object distance dimension), the discussion below will assume that only a single pixel is under consideration, and that this pixel views the target object at the center of the planar laser beam width.

For a fixed focal length imaging lens, the width L of the planar laser beam is a function of the fan/spread angle θ induced by (i) the cylindrical lens element in the PLIM and (ii) the object distance r, as defined by the following expression (9):

$$L = 2r\tan\frac{\theta}{2} \qquad (9)$$

Fig. 1M3 shows a plot of beam width length L versus object distance r calculated using θ = 50°, demonstrating the planar laser beam width increases as a function of increasing object distance.

The height parameter of the planar laser illumination beam "h" is controlled by adjusting the focusing lens 15 between the visible laser diode (VLD) 13 and the cylindrical lens 16, shown in Figs. 1I1 and 1I2. Fig. 1M4 shows a typical plot of planar laser beam height h vs. image distance r for a planar laser illumination beam focused at the farthest object distance in accordance with the principles of the present invention. As shown in Fig. 1M4, the height dimension of the planar laser beam decreases as a function of increasing object distance.

Assuming a reasonable total laser power output of 20 mW from the VLD 13 in each PLIM 11, the values shown in the plots of Figs. 1M3 and 1M4 can be used to determine the power density E_0 of the planar laser beam at the center of its beam width, expressed as a function of object distance. This measure, plotted in Fig. 1N, demonstrates that the use of the laser beam focusing technique of the present invention, wherein the height of the planar laser illumination beam is decreased as the object distance increases, compensates for the increase in beam width in the planar laser illumination beam, which occurs for an increase in object distance. This yields a laser beam power density on the target object which increases as a function of increasing object distance over a substantial portion of the object distance range of the PLIIM system.

Finally, the power density E_0 plot shown in Fig. 1N can be used with expression (1) above to determine the power density on the pixel, E_{pix}. This E_{pix} plot is shown in Fig. 1O. For comparison purposes, the plot obtained when using the beam focusing method of the present invention is plotted in Fig. 1O against a "reference" power density plot E_{pix} which is obtained when focusing the laser beam at infinity, using a collimating lens (rather than a focusing lens 15) disposed after the VLD 13, to produce a collimated-type planar laser illumination beam having a constant beam height of 1 mm over the entire portion of the object distance range of the system. Notably, however, this non-preferred beam collimating technique, selected as the reference plot in Fig. 1O, does not compensate for the above-described effects associated with an increase in planar laser beam width as a function of object distance. Consequently, when using this non-preferred beam focusing technique, the power density of the planar laser illumination beam produced by each PLIM decreases as a function of increasing object distance.

Therefore, in summary, where a fixed or variable focal length imaging subsystem is employed in the PLIIM system hereof, the planar laser beam focusing technique of the present invention described above helps compensate for decreases in the power density of the incident planar illumination beam due to the fact that the width of the planar laser illumination beam increases for increasing object distances away from the imaging subsystem.

Producing A Composite Planar Laser Illumination Beam Having Substantially Uniform Power Density Characteristics In Near And Far Fields, By Additively Combining The Individual Gaussian Power Density Distributions Of Planar Laser Illumination Beams Produced By Planar Laser Illumination Beam Modules (PLIMS) In Planar Laser Illumination Arrays (PLIAs)

Having described the best known method of focusing the planar laser illumination beam produced by each VLD in each PLIM in the PLIIM system hereof, it is appropriate at this juncture to describe how the individual Gaussian power density distributions of the planar laser illumination beams produced a PLIA 6A, 6B are additively combined to produce a composite planar laser illumination beam having substantially uniform power density characteristics in near and far fields, as illustrated in Figs. 1P1 and 1P2.

When the laser beam produced from the VLD is transmitted through the cylindrical lens, the output beam will be spread out into a laser illumination beam extending in a plane along the direction in which the lens has curvature. The beam size along the axis which corresponds to the height of the cylindrical lens will be transmitted unchanged. When the planar laser illumination beam is projected onto a target surface, its profile of power versus displacement will have an approximately Gaussian distribution. In accordance with the principles of the present invention, the plurality of VLDs on each side of the IFD module are spaced out and tilted in such a way that their individual power density distributions add up to produce a (composite) planar laser illumination beam having a magnitude of illumination which is distributed substantially uniformly over the entire working depth of the PLIIM system (i.e. along the height and width of the composite planar laser illumination beam).

The actual positions of the PLIMs along each planar laser illumination array are indicated in Fig. 1G3 for the exemplary PLIIM system shown in Figs. 1G1 through 1I2. The mathematical analysis used to analyze the results of summing up the individual power density functions of the PLIMs at both near and far working distances was carried out using the Matlab™ mathematical modeling program by Mathworks, Inc. (http://www.mathworks.com). These results are set forth in the data plots of Figs. 1P1 and 1P2. Notably, in these data plots, the total power density is greater at the far field of the working range of the PLIIM system. This is because the VLDs in the PLIMs are focused to achieve minimum beam width thickness at the farthest object distance of the system, whereas the beam height is somewhat greater at the near field region. Thus, although the far field receives less illumination power at any given location, this power is concentrated into a smaller area, which results in a greater power density within the substantially planar extent of the planar laser illumination beam of the present invention.

When aligning the individual planar laser illumination beams (i.e. planar beam components) produced from each PLIM, it will be important to ensure that each such planar laser illumination beam spatially coincides with a section of the FOV of the imaging subsystem, so that the composite planar laser illumination beam produced by the individual beam components spatially coincides with the FOV of the imaging subsystem throughout the entire working depth of the PLIIM system.

Methods Of Reducing The RMS Power Of Speckle-Noise Patterns Observed At The Linear Image Detection Array Of A PLIIM-Based System When Illuminating Objects Using A Planar Laser Illumination Beam

In the PLIIM-based systems disclosed herein, five (5) general classes of techniques and apparatus have been developed to effectively destroy or otherwise substantially reduce the spatial and/or temporal coherence of the laser illumination sources used to generate planar laser illumination beams (PLIBs) within such systems, and thus enable time-varying speckle-noise patterns to be produced at the image detection arrays thereof and temporally and/or spatially averaged over the photo-integration time period thereof, to thereby reducing the RMS power of speckle-noise patterns observed (i.e. detected) at the image detection array.

In general, the power-density spectrum of speckle-noise patterns in PLIIM-based systems can be reduced by using any combinataion of the following techniques: (1) by using a multiplicity of real laser (diode) illumination sources in the planar laser illumination arrays (PLIIM) of the PLIIM-based system; (2) by using a (secondary) cylindrical lens array 299 after each PLIA to create a multiplicity of virtual illumination sources illuminating the target object, as illustrated in the various embodiments of the present invention disclosed herein; and/or (3) by employing any of the four generalized spatial-intensity and temporal-intensity modulation techniques of the present invention described in detail below. Notably, the speckle-noise reduction coefficient of the PLIIM-based system will be inversely proportional to the square root of the number of statistically independent real and virtual sources of laser illumination created by the speckle-noise pattern reduction techniques employed within the PLIIM-based system.

In Figs. 1I1 through 1I11C, a first generalized method of speckle-noise pattern reduction in accordance with the principles of the present invention and particular forms of apparatus therefor are schematically illustrated. This generalized method involves reducing the spatial-coherence of the PLIB before it illuminates the target (i.e. object).

In Figs. 1I12 through 1I15C, a second generalized method of speckle-noise pattern reduction in accordance with the principles of the present invention and particular forms of apparatus therefor are schematically illustrated. This generalized method involves reducing the temporal-coherence of the PLIB before it illuminates the target (i.e. object).

In Figs.1I17 through 1I19D, a third generalized method of speckle-noise pattern reduction in accordance with the principles of the present invention and particular forms of apparatus therefor are schematically illustrated. This generalized method involves reducing the spatial-coherence of the PLIB before it illuminates the target (i.e. object).

In Figs. 1I20 through 1I22B, a fourth generalized method of speckle-noise pattern reduction in accordance with the principles of the present invention and particular forms of apparatus therefor are schematically illustrated. This generalized method involves reducing the spatial-coherence of the PLIB after the transmitted PLIB reflects and/or scatters off the illuminated the target (i.e. object).

In Figs. 1I23 through 1I25, a fifth generalized method of speckle-noise pattern reduction in accordance with the principles of the present invention and particular forms of apparatus therefor are schematically illustrated. This generalized method involves reducing the temporal-coherence of the PLIB after the transmitted PLIB reflects and/or scatters off the illuminated the target (i.e. object).

Notably, each of the five generalized methods of speckle-noise pattern reduction to be described below are assumed to satisfy the general conditions under which the random "speckle-noise" process is Gaussian in character. These general conditions have been clearly identified by J.C. Dainty, et al, in page 124 of "Laser Speckle and Related Phenomena", supra, and are restated below for the sake of completeness: (i) that the standard deviation of the surface height fluctuations in the scattering surface (i.e. target object) should be greater than λ, thus ensuring that the phase of the scattered wave is uniformly distributed in the range 0 to 2π; and (ii) that a great many independent scattering centers (on the target object) should contribute to any given point in the image detected at the image detector.

First Generalized Method Of Speckle-Noise Pattern Reduction And Particular Forms Of Apparatus Therefor Based On Reducing The Spatial-Coherence Of The Planar Laser Illumination Beam Before It Illuminates The Target Object

Referring to Figs. 1I1 through 1I11C, the first generalized method of speckle-noise pattern reduction and particular forms of apparatus therefor will be described. This generalized method is based on the principle of spatially modulating the "transmitted" planar laser illumination beam (PLIB) prior to illuminating a target object (e.g. package) therewith so that the object is illuminated with a spatially coherent-reduced planar laser beam and, as a result, numerous substantially different time-varying speckle-noise patterns are produced and detected over the photo-integration time period of the image detection array (in the IFD subsystem), thereby allowing these speckle-noise patterns to be temporally averaged and possibly spatially averaged over the photo-integration time period and the the RMS power of observable speckle-noise pattern reduced. This method can be practiced with any of the PLIM-based systems of the present invention disclosed herein, as well as any system constructed in accordance with the general principles of the present invention.

Whether any significant spatial averaging can occur in any particular embodiment of the present invention will depend on the relative dimensions of: (i) each element in the image detection array; and (ii) the physical dimensions of the speckle blotches in a given speckle-noise pattern which will depend on the standard deviation of the surface height fluctuations in the scattering surface or target object, and the wavelength of the illumination source λ). As the size of each image detection element is made larger, the image resolution of the image detection array will decrease, with an accompanying increase in spatial averaging. Clearly, there is a tradeoff to be decided upon in any given application.

As illustrated at Block A in Fig. 1I2B, the first step of the first generalized method shown in Figs. 1I1 through 1I11C involves spatially modulating the transmitted planar laser illumination beam (PLIB) along the planar extent thereof according to a (random or periodic) spatial phase modulation function (SPMF) prior to illumination of the target object with the PLIB, so as to modulate the phase along the wavefront of the PLIB and produce numerous substantially different time-varying speckle-noise pattern at the image detection array of the IFD

Subsystem during the photo-integration time period thereof. As indicated at Block B in Fig. 1I2B, the second step of the method involves temporally and spatially averaging the numerous substantially different speckle-noise patterns produced at the image detection array in the IFD Subsystem during the photo-integration time period thereof.

When using the first generalized method, the target object is repeatedly illuminated with laser light apparently originating from different points (i.e. virtual illumination sources) in space over the photo-integration period of each detector element in the linear image detection array of the PLIIM system, during which reflected laser illumination is received at the detector element. As the relative phase delays between these virtual illumination sources are changing over the photo-integration time period of each image detection element, these virtual sources are effectively rendered spatially incoherent with each other. On a time-average basis, these time-varying speckle-noise patterns are temporally (and possibly spatially) averaged during the photo-integration time period of the image detection elements, thereby reducing the RMS power of the speckle-noise pattern (i.e. level) observed thereat. As speckle noise patterns are roughly uncorrelated at the image detection array, the reduction in speckle-noise power should be proportional to the square root of the number of independent virtual laser illumination sources contributing to the illumination of the target object and formation of the image frame thereof. As a result of the present invention, image-based bar code symbol decoders and/or OCR processors operating on such digital images can be processed with significant reductions in error.

The first generalized method above can be explained in terms of Fourier Transform optics. When spatial-intensity modulating the transmitted PLIB by a periodic or random spatial phase modulation function (SPMF), while satisfying conditions (i) and (ii) above, a spatial phase modulation process occurs on the spatial domain. This spatial phase modulation process is equivalent to mathematically multiplying the transmitted PLIB by the spatial phase modulation function. This multiplication process on the spatial domain is equivalent on the spatial-frequency domain to the convolution of the Fourier Transform of the spatial phase modulation function with the Fourier Transform of the transmitted PLIB. On the spatial-frequency domain, this convolution process generates spatially-incoherent (i.e. statistically-uncorrelated) spectral components which are permitted to spatially-overlap at each detection element of the image detection array (i.e. on the spatial domain) and produce time-varying speckle-noise patterns which are temporally (and possibly) spatially averaged during the photo-integration time period of each detector element, to reduce the RMS power of the speckle-noise pattern observed at the image detection array.

In general, various types of spatial phase modulation techniques can be used to carry out the first generalized method including, for example: mechanisms for moving the relative position/motion of a cylindrical lens array and laser diode array, including reciprocating a pair of rectilinear cylindrical lens arrays relative to each other, as well as rotating a cylindrical lens array ring structure about each PLIM employed in the PLIIM-based system; rotating phase modulation discs having multiple sectors with different refractive indices to effect different degrees of phase delay along the wavefront of the PLIB transmitted (along different optical paths) towards the

object to be illuminated; acousto-optical Bragg-type cells for enabling beam steering using ultrasonic waves; ultrasonically-driven deformable mirror structures; a LCD-type spatial phase modulation panel; and other spatial phase modulation devices. Several of these spatial light modulation (SLM) mechanisms will be described in detail below.

<u>Apparatus Of The Present Invention For Micro-Oscillating A Pair Of Refractive Cylindrical Lens Arrays To Spatial Phase Modulate The Planar Laser Illumination Beam Prior To Target Object Illumination</u>

In Figs. 1I3A through 1I3D, there is shown an optical assembly 300 for use in any PLIIM-based system of the present invention. As shown, the optical assembly 300 comprises a PLIA 6A with a pair of refractive-type cylindrical lens arrays 301A and 301B, and an electronically-controlled mechanism 302 for micro-oscillating the pair cylindrical lens arrays 301A and 301B along the planar extent of the PLIB. In accordance with the first generalized method, the pair of cylindrical lens arrays 301A and 301B are micro-oscillated, relative to each other (out of phase by 90 degrees) using two pairs of ultrasonic (or other motion-imparting) transducers 303A, 303B, and 304A, 304B arranged in a push-pull configuration so that individual beam components within the PLIB 305 transmitted through the cylindrical lens arrays are micro-oscillated (i.e. moved) along the planar extent thereof by an amount of distance Δx or greater at a velocity v(t) which causes the phase along the wavefronts of the PLIB to be modulated and numerous (e.g. 25 or more) substantially different time-varying speckle-noise patterns generated at the image detection array of the IFD Subsystem during the photo-integration time period thereof so that the numerous time-varying speckle-noise patterns produced at the image detection array are temporally (and possibly spatially) averaged during the photo-integration time period thereof, thereby reducing the RMS power of speckle-noise patterns observed at the image detection array.

As shown in Fig. 1I3C, an array support frame 305 with a light transmission window 306 and accessories 307A and 307B for mounting pairs of ultrasonic transducers 303A, 303B and 304A, 304B, is used to mount the pair of cylindrical lens arrays 301A and 301B in a relative reciprocating manner, and thus permitting micro-oscillation in accordance with the principles of the present invention. In 1I3D, the pair of cylindrical lens arrays 301A and 301B are shown configured between pairs of ultrasonic transducers 303A, 303B and 304A, 304B (or flexural elements driven by voice-coil type devices) operated in a push-pull mode of operation. By employing dual cylindrical lens arrays in this optically assembly, the transmitted PLIB is spatial phase modulated in a continual manner during object illumination operations. By virtue of this optical assembly design, when one cylindrical lens array is momentarily stationary during beam direction reversal, the other cylindrical lens array is moving in an independent manner, thereby causing the transmitted PLIB 307 to be spatial phase modulated even at times when one cylindrical lens array is reversing its direction (i.e. momentarily at rest).

In the illustrative embodiment, each cylindrical lens array 301A and 301B is realized as a lenticular screen having 64 cylindrical lenslets per inch. For a speckle-noise power reduction of five (5x), it was determined experimentally that about 25 or more substantially different speckle-noise patterns must be generated during a photo-integration time period of $1/10000^{th}$ second, and that a 125 micron shift (Δx) in the cylindrical lens arrays was required, thereby requiring an array velocity of about 1.25 meters/second. Using a sinusoidal function to drive each cylindrical lens array, the array velocity is described by the equation $V=A\omega\sin(\omega t)$, where $A=3x10^{-3}$ meters and $\omega=370$ radians/second (i.e. 60Hz) providing about a peak array velocity of about 1.1 meter/second. Notably, one can increase the number of substantially different speckle-noise patterns produced during the photo-integration time period of the image detection array by either (i) increasing the spatial period of each cylindrical lens array, and/or (ii) increasing the relative velocity cylindrical lens array(s) and the PLIB transmitted therethrough during object illumination operations. Increasing either of this parameters will have the effect of increasing the spatial gradient of the spatial phase modulation function (SPMF) of the optical assembly, causing steeper transistions in phase delay along the wavefront of the PLIB, as the cylindrical lens arrays move relative to the PLIB being transmitted therethrough. Expectedly, this will generate more components with greater magnitude values on the spatial-frequency domain of the system, thereby producing more independent virtual spatially-incoherent illumination sources in the system. This will tend to reduce the RMS power of speckle-noise patterns observed at the image detection array.

<u>Conditions For Producing Uncorrelated Time-Varying Speckle-Noise Pattern Variations At The Image Detection Array of The IFD Subsystem</u>

In general, each method of speckle-noise reduction according to the present invention requires modulating the spatial phase, the spatial intensity, and/or the temporal intensity of the transmitted PLIB so that the phase along the wavefront of the PLIB is modulated and numerous substantially different time-varying speckle-noise patterns are generated at the image detection array each photo-integration time period/interval thereof. By achieving this condition, the planar laser illumination beam (PLIB), either transmitted to the target object, or reflected therefrom and received by the IFD subsystem, is rendered partially coherent or coherent-reduced. This ensures that the speckle-noise patterns produced at the image detection array are statistically uncorrolated, and therefore can be temporally and possibly spatially averaged at each image detection element during the photo-integration time period thereof, thereby reducing the RMS power of the speckle-noise pattern observed at the image detection array. The amount of RMS power reduction that is achievable at the image detection array or the system is therefore dependent upon the number of substantially different time-varying speckle-noise patterns generated at the image detection array during its photo-integration time period. For any particular speckle-noise reduction apparatus of the present invention, a number parameters will factor into determining the numer of substantially different time-varying speckle-noise patterns

that must be generated each photo-integration time period to achieve a particular degree of reduction in the RMS power of speckl-noise patterns at the image detection array.

Referring to Fig. 1I3E, a geometrical model of a subsection of the optical assembly of Fig. 1I3A is shown. This simplified model illustrates the first order parameters involved in the PLIB spatial phase modulation process, and also the relationship among such parameters which ensures that at least one cycle of speckle-noise pattern variation will be produced at the image detection array of the IFD (i.e. camera) Subsystem. As shown, this simplied model is derived by taking a simple case example, where only two virtual laser illumination sources (such as those generated by two cylindrical lenslets) are illuminating a target object. In practice, there will be numerous virtual laser beam sources by virtue of the fact that the cylindrical lens array has numerous lenslets (e.g 64 lenslets/inch) and cylindrical lens array is micro-oscillated at a particular velocity with respect to the PLIB as the PLIB is being transmitted therethrough.

In the simplied case shown in Fig. 1I3E, the speckle-noise pattern viewed by the pair of cylindrical lens elements of the imaging array will become uncorrelated with respect to the original speckle-noise pattern (produced by the real laser illumination source) when the difference in phase among the wavefront of the individual beam components is on the order of 1/2 of the laser illumination wavelength λ. For the case of a moving cylindrical lens array, as shown in Fig. 1I3A, this decorrolation condition is when:

$$\Delta x > \lambda D / 2 P$$

wherein, Δx is the motion of the cylindrical lens array, λ is the characteristic wavelength of the laser illumination source, D is the distance from the laser diode (i.e. source) to the cylindrical lens array, and P is the separation of the lenslets within the cylindrical lens array. This condition ensures that one cycle of speckle-noise pattern variation will occur at the image detection array of the IFD Subsystem for each movement of the cylindrical lens array by distance Δx. This implies that, for the apparatus of Fig. 1I3A, the time-varying speckle-noise patterns detected by the image detection array of IFD subsystem will become statistically uncorrelated (i.e. substantially different) with respect to the original speckle-noise pattern produced by the real laser illumination sources, when the spatial gradient in the phase of the beam wavefront is greater than or equal to $\lambda/2P$.

Conditions For Temporally Averaging Time-Varying Speckle-Noise Patterns At The Image Detection Array of The IFD Subsystem

To ensure additive cancellation of the uncorrelated time-varying speckle-noise patterns detected at the (coherent) image detection array, it is necessary that numerous substantially different (i.e. uncorrolated) time-varying speckle-noise patterns are generated during each the photo-integration time period. In the case of optical system of Fig. 1I3A, the following parameters will influence the number of substantially different time-varying speckle-noise

patterns generated at the image detection array during each photo-integration time period thereof: (i) the spatial period of each refractive cylindrical lens array; (ii) the width dimension of each cylindrical lenset; (iii) the length of each lens array; (iv) the velocity thereof; and (v) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (1) through (iv) will factor into the specification of the spatial phase modulation function (SPMF) of the system. In general, if the system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrolated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Adjustment of the above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at hand.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I3A, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval of the image detection array can be experimentally determined without undue experimentation. However, it should be noted that this minimum sampling parameter threshold is expressed on the time domain, and that expectedly, the lower threshold for this sample number at the image detection (i.e. observation) end of the PLLIM-based system, for a particular degree of speckle-noise power reduction, can be expressed mathamatically in terms of (i) the spatial gradient of the spatial phase modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

By ensuring that these two conditions are satisfied to the best degree possible (at the planar laser illumination subsystem and the IFD subsystem) will ensure optimal reduction in speckle-noise patterns observed at the image detector of the PLIIM-based system of the present invention. In general, the reduction in the RMS power of observable speckle-noise pattern will be inversely proportional to the square root of the number of statistically uncorolated real and virtual illumination sources created by the speckle-noise reduction technique of the present invention. Figs. 1I3F and 1I3G illustrate that significant mitigation in speckle-noise patterns can be achieved when using the particular apparatus of Fig. 1I3A in accordance with the first generalized speckle-noise pattern reduction method illustrated in Figs. 1I1 through 1I2B.

<u>Apparatus Of The Present Invention For Micro-Oscillating A Pair Of Light Diffractive (e.g. Holographic) Cylindrical Lens Arrays To Spatial Phase Modulate The Planar Laser Illumination Beam Prior To Target Object Illumination</u>

In Fig. 1I4A, there is shown an optical assembly 310 for use in any PLIIM-based system of the present invention. As shown, the optical assembly 310 comprises a PLIA 6A, 6B with a pair of (holographically-fabricated) diffractive-type cylindrical lens arrays 311A and 311B, and an electronically-controlled PLIB micro-oscillation mechanism 312 for micro-oscillating the cylindrical lens arrays 311A and 311B along the planar extent of the PLIB. In accordance with the first generalized method, the pair of cylindrical lens arrays 311A and 311B are micro-

oscillated, relative to each other (out of phase by 90 degrees) using two pairs of ultrasonic transducers 313A, 313B and 314A, 314B arranged in a push-pull configuration so that individual beam components within the transmitted PLIB 315 are micro-oscillated (i.e. moved) along the planar extent thereof by an amount of distance Δx or greater at a velocity v(t) which causes the phase along the wavefront of the transmitted PLIB to be spatially modulated and numerous substantially different (i.e. uncorrolated) time-varying speckle-noise patterns generated at the image detection array of the IFD Subsystem during the photo-integration time period thereof so that the numerous time-varying speckle-noise patterns produced at the image detection array can be temporally (and possibly spatially) averaged during the photo-integration time period thereof, thereby reducing the RMS power of speckle-noise patterns observed at the image detection array.

As shown in Fig. 1I4C, an array support frame 316 with a light transmission window 317 and recesses 318A and 318B is used to mount the pair of cylindrical lens arrays 311A and 311B in a relative reciprocating manner, and thus permitting micro-oscillation in accordance with the principles of the present invention. In 1I4D, the pair of cylindrical lens arrays 311A and 311B are shown configured between a pair of ultrasonic transducers 313A, 313B and 314A, 314B (or flexural elements driven by voice-coil type devices) mounted in recesses 318A and 318B, respectively, and operated in a push-pull mode of operation. By employing dual cylindrical lens arrays in this optically assembly, the transmitted PLIB 315 is spatial phase modulated in a continual manner during object illumination operations. By virtue of this optical assembly design, when one cylindrical lens array is momentarily stationary during beam direction reversal, the other cylindrical lens array is moving in an independent manner, thereby causing the transmitted PLIB to be spatial phase modulated even when the cylindrical lens array is reversing its direction.

In the case of optical system of Fig. 1I4A, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated at the image detection array during each photo-integration time period thereof: (i) the spatial period of (each) HOE cylindrical lens array; (ii) the width dimension of each HOE; (iii) the length of each HOE lens array; (iv) the velocity thereof; and (v) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (1) through (iv) will factor into the specification of the spatial phase modulation function (SPMF) of this speckle-noise reduction subsystem design. In general, if the PLIIM-based system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrolated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Adjustment of the above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at hand.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I4A, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval of the image detection array can be experimentally determined without undue experimentation. However, for a particular degree of

speckle-noise power reduction, it is expected that the lower threshold for this sample number at the image detection array can be expressed mathamatically in terms of (i) the spatial gradient of the spatial phase modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

<u>Apparatus Of The Present Invention For Micro-Oscillating A Pair Of Reflective Elements Relative To A Stationary Refractive Cylindrical Lens Array To Spatial Phase Modulate A Planar Laser Illumination Beam Prior To Target Object Illumination</u>

In Fig. 1I5A, there is shown an optical assembly 320 for use in any PLIIM-based system of the present invention. As shown, the optical assembly comprises a PLIA 6A, 6B with a stationary (refractive-type or diffractive-type) cylindrical lens array 321, and an electronically-controlled micro-oscillation mechanism 322 for micro-oscillating, relative to a stationary refractive-type cylindrical lens array 321 and a stationary reflective element (i.e. mirror element) 323, a pair of reflective-elements 324A and 324B along the planar extent of the PLIB. In accordance with the first generalized method, the pair of reflective elements 324A and 324B are micro-oscillated relative to each other (at 90 degrees out of phase) using two pairs of ultrasonic transducers 325A, 325B and 326A, 326B arranged in a push-pull configuration, so that the transmitted PLIB is micro-oscillated (i.e. move) along the planar extent thereof (i) by an amount of distance Δx or greater at a velocity v(t) which causes the phase along the wavefront of the transmitted PLIB to be modulated and numerous substantially different time-varying speckle-noise patterns generated at the image detection array of the IFD Subsystem during the photo-integration time period thereof so that these numerous time-varying speckle-noise patterns can be temporally and possibly spatially averaged during the photo-integration time period thereof, thereby reducing the RMS power of the speckle-noise patterns observed at the image detection array.

As shown in Fig. 1I5B, the pair of reflective elements 324A and 324B are pivotally connected to a common point 327 on support post 328 or lens array frame 329 in a relative reciprocating manner, and thus permit micro-oscillation thereof along the planar extent of the PLIB in accordance with the principles of the present invention. In 1I5D, the pair of reflective elements 324A and 324B are shown configured between two pairs of ultrasonic transducers 325A, 325B and 326A, 326B (or flexural elements driven by voice-coil type devices) supported on posts 330A, 330B operated in a push-pull mode of operation. By employing dual reflective elements in this optical assembly, the transmitted PLIB 331 is spatial phase modulated in a continual manner during object illumination operations. By virtue of this optical assembly design, when one reflective element is momentarily stationary when reversing its direction, the other reflective element is moving in an independent manner, thereby causing the transmitted PLIB 331 to be continually spatial phase modulated.

In the case of optical system of Fig. 1I5A, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated at the image detection array during each photo-integration time period thereof: (i) the spatial period of the cylindrical lens array; (ii) the width dimension of each lenslet; (iii) the length of each HOE lens array; (iv) the length and angular velocity of the reflector elements; and (v) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (1) through (iv) will factor into the specification of the spatial phase modulation function (SPMF) of this speckle-noise reduction subsystem design. In general, if the system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrolated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Adjustment of the above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at hand.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I5A, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval of the image detection array can be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this sample number at the image detection array can be expressed mathamatically in terms of (i) the spatial gradient of the spatial phase modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

Apparatus Of The Present Invention For Micro-Oscillating The Planar Laser Illumination (PLIB) Using An Acoustic-Optic Modulator To Spatial Phase Modulate Said PLIB Prior To Target Object Illumination

In Fig. 1I6A, there is shown an optical assembly 340 for use in any PLIIM-based system of the present invention. As shown, the optical assembly 340 comprises a PLIA 6A, 6B with a cylindrical lens array 341, and an acousto-optical (i.e. Bragg Cell) beam deflection mechanism 343 for micro-oscillating the PLIB 343 prior to illuminating the target object. In accordance with the first generalized method, the PLIB 344 is micro-oscillated by an acousto-optical (i.e. Bragg Cell) beam deflection device 345 as acoustical waves (signals) 346 propagate through the electro-acoustical device transverse to the direction of transmission of the PLIB 344, so as to micro-oscillate (i.e. move) the beam components of the composite PLIB 344 along the planar extent thereof by an amount of distance Δx or greater at a velocity v(t) which causes the phase along the wavefront of the transmitted PLIB to be modulated and numerous substantially different time-varying speckle-noise patterns generated at the image detection array during the photo-integration time period thereof, and the numerous time-varying speckle-noise patterns temporally and possibly spatially averaged at the image detection array during each the photo-

integration time period thereof. As shown, the acousto-optical beam deflective panel 345 is driven by control signals supplied by electrical circuitry under the control of camera control computer 22.

In the illustrative embodiment, beam deflection panel 345 is made from an ultrasonic cell comprising: a pair of spaced-apart optically transparent panels 346A and 346B, containing an optically transparent, ultrasonic wave carrying fluid, e.g. toluene (i.e. CH_3 C_6 H_5) 348; a pair of end panels 348A and 348B cemented to the side and end panels to contain the ultrasonic wave carrying fluid 348; an array of piezoelectric transducers 349 mounted through end wall 349A; and an ultrasonic-wave dampening material 350 disposed at the opposing end wall panel 349B, on the inside of the cell, to avoid reflections of the ultrasonic wave at the end of the cell. Electronic drive circuitry is provided for generating electrical drive signals for the acoustical wave cell 345 under the control of the camera control computer 22. In the illustrative embodiment, these electrical drives signals are provided to the piezoelectric transducers 349 and result in the generation of an ultrasonic wave that propagates at a phase velocity through the cell structure, from one end to the other, causing a modulation of the refractive index of the ultrasonic wave carrying fluid 348, and thus a modulation of the phase along the wavefront of the transmitted PLIB, thereby causing the same to be periodically swept across the cylindrical lens array 341. The resulting PLIB is transmitted from the the cylindrical lens array 341 and illuminates its target object. After reflecting therefrom, the received PLIB produces numerous substantially different time-varying speckle-noise patterns on the image detection array of the PLIIM-based system during the photo-integration time period thereof. These time-varying speckle-noise patterns are temporally and spatially averaged at the image detection array, thereby reducing the power of speckle-noise patterns observable at the image detection array.

In the case of optical system of Fig. 1I6A, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated at the image detection array during each photo-integration time period thereof: (i) the spatial frequency of the cylindrical lens array; (ii) the width dimension of each lenslet; (iii) the temporal and velocity characteristics of the acoustical wave 348 propagating through the acousto-optical cell structure 345; (iv) the optical density characteristics of the ultrasonic wave carrying fluid 348; and (v) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (1) through (iv) will factor into the specification of the spatial phase modulation function (SPMF) of this speckle-noise reduction subsystem design. In general, if the system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrolated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof.

One can expect an increase the number of substantially different speckle-noise patterns produced during the photo-integration time period of the image detection array by either: (i) increasing the spatial period of each cylindrical lens array; (ii) the temporal period and rate of repeetition of the acoustical waveform propagating along the cell structure 345; and/or (iii) increasing the relative velocity between the stationary cylindrical lens array and the PLIB

transmitted therethrough during object illumination operations, by increasing the velocity of the acoustical wave propagating through the acousto-optical cell 345. Increasing either of these parameters should have the effect of increasing the spatial gradient of the spatial phase modulation function (SPMF) of the optical assembly, causing steeper transistions in phase delay along the wavefront of the composite PLIB, as it is transmitted through cylindrical lens array 341 in response to the propagation of the acoustical wave along the cell structure 345. Expectedly, this should generate more components with greater magnitude values on the spatial-frequency domain of the system, thereby producing more independent virtual spatially-incoherent illumination sources in the system. This should tend to reduce the RMS power of speckle-noise patterns observed at the image detection array.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I6A, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval of the image detection array can be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this "sample number" at the image detection array can be expressed mathamatically in terms of (i) the spatial gradient of the spatial phase modulated PLIB and/or the time derivative of the phase modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

Notably, in an alternative embodiment, the acousto-optical cell 345 may be positioned before the cylindrical lens array 341 without alternating the basic functions of this speckle-noise power reduction subsytem.

<u>Apparatus Of The Present Invention For Micro-Oscillating The Planar Laser Illumination (PLIB) Using A Piezo-Electric Driven Deformable Mirror Structure To Spatial Phase Modulate Said PLIB Prior To Target Object Illumination</u>

In Fig. 1I7A, there is shown an optical assembly 360 for use in any PLIIM-based system of the present invention. As shown, the optical assembly 360 comprises a PLIA 6A, 6B with a cylindrical lens array 361 (supported within a frame 362), and an electro-mechanical PLIB micro-oscillation mechanism 363 for micro-oscillating the PLIB prior to transmission to the target object to be illuminated. In accordance with the first generalize method, the composite PLIB produced by the cylindrical lens array 361 (e.g. operating according to refractive, diffractive and/or reflective principles) is reflected off a piezo-electrically driven deformable mirror (DM) structure 364 arranged in front of cylindrical lens array 361, back towards a stationary beam folding mirror 365 mounted above the cylindrical lens array 361 (by support posts 366A, 366B and 366C) and then reflected thereoff towards the target object. During PLIB transmission in the case of an illustrative embodiment involving a high-speed tunnel scanning system, the surface of the DM structure 364 (Δx) is periodically deformed at frequencies in the 100kHz range and at few microns amplitude, to produce moving ripples aligned along the

direction that is perpendicular to planar extent of the PLIB (i.e. along its beam spread). These moving ripples cause the beam components within the PLIB 367 to be micro-oscillated (i.e. moved) along the planar extent thereof by an amount of distance Δx or greater at a velocity v(t) which modules the phase among the wavefront of the transmitted PLIB and produces numerous substantially different time-varying speckle-noise patterns at the image detection array during the photo-integration time period thereof, so that these numerous substantially different time-varying speckle-noise patterns can be temporally and possibly spatially averaged during each photo-integration time period of the image detection array. Fig. 1I7A shows the optical path which the PLIB travels while undergoing phase modulation by the piezo-electrically driven DM structure 364 during target object illumination operations.

In the case of optical system of Fig. 1I7A, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated at the image detection array during each photo-integration time period thereof: (i) the spatial period of the cylindrical lens array; (ii) the width dimension of each lenslet; (iii) the temporal and velocity characteristics of the surface deformations produced along the DM structure 364; and (v) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (1) through (iv) will factor into the specification of the spatial phase modulation function (SPMF) of this speckle-noise reduction subsystem design.

In general, if the system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrolated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Notably, one can expect an increase the number of substantially different speckle-noise patterns produced during the photo-integration time period of the image detection array by either: (i) increasing the spatial period of each cylindrical lens array; (ii) the spatial gradient of the surface deformations produced along the DM structure 364; and/or (iii) increasing the relative velocity between the stationary cylindrical lens array and the PLIB transmitted therethrough during object illumination operations, by increasing the velocity of the surface deformations along the DM structure 364. Increasing either of these parameters should have the effect of increasing the spatial gradient of the spatial phase modulation function (SPMF) of the optical assembly, causing steeper transistions in phase delay along the wavefront of the composite PLIB, as it is transmitted through cylindrical lens array in response to the propagation of the acoustical wave along the cell. Expectedly, this should generate more components with greater magnitude values on the spatial-frequency domain of the system, thereby producing more independent virtual spatially-incoherent illumination sources in the system. This should tend to reduce the RMS power of speckle-noise patterns observed at the image detection array.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I7A, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval of the image detection array can be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this "sample number"

at the image detection array can be expressed mathamatically in terms of (i) the spatial gradient of the spatial phase modulated PLIB and/or the time derivative of the phase modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

Notably, in an alternative embodiment, the DM structure 364 may be positioned before the cylindrical lens array 361 without alternating the basic functions of this speckle-noise power reduction subsytem.

<u>Apparatus Of The Present Invention For Micro-Oscillating The Planar Laser Illumination (PLIB) Using A Refractive-Type Phase-Modulation Disc To Spatial Phase Modulate Said PLIB Prior To Target Object Illumination</u>

In Fig. 1I8A, there is shown an optical assembly 370 for use in any PLIIM-based system of the present invention. As shown, the optical assembly 370 comprises a PLIA 6A, 6B with cylindrical lens array 371, and an optically-based PLIB micro-oscillation mechanism 372 for micro-oscillating the PLIB 373 transmitted towards the target object prior to illumination. In accordance with the first generalize method, the PLIB micro-oscillation mechanism 372 is realized by a refractive-type phase-modulation disc 374, rotated by an electric motor 375 under the control of the camera control computer 22. As shown in Figs. 1I8B and 1I8D, the PLIB form PLIA 6A is transmitted perpendicularly through a sector of the phase modulation disc 374, as shown in Fig. 1I8D. As shown in Fig. 1I8D, the disc comprises numerous sections 376, each having refractive indices that vary sinusoidally at different angular positions along the disc. Preferably, the light transmittivity of each sector is substantially the same, as only spatial phase modulation is the desired light control function to be performed by this subsystem. Also, to ensure that the phase along the wavefront of the PLIB is modulated along its planar extent, each PLIA 6A, 6B should be mounted relative to the phase modulation disc so that the sectors 376 move perpendicular to the plane of the PLIB during disc rotation. As shown in Fig. 1I8D, this condition can be best achieved by mounting each PLIA 6A, 6B as close to the outer edge of its phase modulation disc as possible where each phase modulating sector moves substantially perpdendical to the plane of the PLIB as the disc rotates about its axis of rotation.

During system operation, the refractive-type phase-modulation disc 374 is rotated about its axis through the composite PLIB 373 so as to modulate the phase along the wavefront of the PLIB and produce numerous substantially different time-varying speckle-noise patterns at the image detection array of the IFD Subsystem during the photo-integration time period thereof, so that these numerous time-varying speckle-noise patterns can be temporally and possibly spatially averged during each photo-integration time period of the image detection array. As shown in Fig. 1I8E, the electric field components produced from the rotating refractive disc sections 371 and its neighboring cylindrical lens elements 371 contribute to the resultant time-varying (uncorrelated) electric field intensity produced at each detector element in the image detection array of the IFD Subsystem.

In the case of optical system of Fig. 1I8A, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated at the image detection array during each photo-integration time period thereof: (i) the spatial period of the cylindrical lens array; (ii) the width dimension of each lenslet; (iii) the length of the lens array in relation to the radius of the phase modulation disc 374; (iv) the tangential velocity of the phase modulation elements passing through the PLIB; and (v) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (1) through (iv) will factor into the specification of the spatial phase modulation function (SPMF) of this speckle-noise reduction subsystem design. In general, if the system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrolated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Adjustment of the above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at hand.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I8A, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval of the image detection array can be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this sample number at the image detection array can be expressed mathamatically in terms of (i) the spatial gradient of the spatial phase modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

Apparatus Of The Present Invention For Micro-Oscillating The Planar Laser Illumination (PLIB) Using A Phase-Only Type LCD-Based Phase Modulation Panel To Spatial Phase Modulate Said PLIB Prior To Target Object Illumination

As shown in Figs. 18F and 18G, the general phase modulation principles embodied in the apparatus of Fig. 1I8A can be applied in the design the optical assembly for reducing the RMS power of speckle-noise patterns observed at the image detection array of a PLIIM-based system. As shown in Figs. 1I8F and 1I8G, optical assembly 700 comprises: a backlit transmissive-type phase-only LCD (PO-LCD) phase modulation panel 701 mounted slightly beyond a PLIA 6A, 6B to intersect the composite PLIB 702; and a cylindrical lens array 703 supported in frame 704 and mounted closely to, or against phase modulation panel 701. The phase modulation panel 701 comprises an array of vertically arranged phase modulating elements or strips 705, each made from birefrigent liquid crystal material. In the illustrative embodiment, phase modulation panel 701 is constructed from a conventional backlit transmission-type LCD panel. Under the control of camera control computer, programmed drive voltage circuitry 706 supplies a set of phase control voltages to the array 705 so as to controllably vary the drive voltage applied across the pixels associated with each predefined phase modulating element 705. Each phase

modulating element is assigned a particular phase coding so that periodic or random micro-shifting of PLIB 708 is achieved along its planar extent prior to transmission through cylindrical lens array 703. During system operation, the phase-modulation panel 701 is driven by applying contol voltages applied across each element 705 so as to modulate the phase along the wavefront of the PLIB, and produce numerous substantially different time-varying speckle-noise patterns at the image detection array (of the accompanying IFD subsytem) during the photo-integration time period thereof so that these time-varying speckle-noise patterns can be temporally and possibly spatially averged thereover, thereby reducing the RMS power of speckle-noise patterns observed at the image detection array.

In the case of optical system of Fig. 1I8F, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated at the image detection array during each photo-integration time period thereof: (i) the spatial period of the cylindrical lens array 703; (ii) the width dimension of each lenslet thereof; (iii) the length of the lens array in relation to the radius of the phase modulation panel 701; (iv) the speed at which the birefringence of each modulation element 705 is electrically switched during the photo-integration time period of the image detection array; and (v) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (1) through (iv) will factor into the specification of the spatial phase modulation function (SPMF) of this speckle-noise reduction subsystem design. In general, if the system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrolated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Adjustment of the above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at hand.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I8F, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval of the image detection array can be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this sample number at the image detection array can be expressed mathamatically in terms of (i) the spatial gradient of the spatial phase modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

<u>Apparatus Of The Present Invention For Micro-Oscillating The Planar Laser Illumination (PLIB) Using A Refractive-Type Cylindrical Lens Array Ring Structure To Spatial Phase Modulate Said PLIB Prior To Target Object Illumination</u>

In Fig. 1I9A, there is shown a pair of optical assemblies 380A and 380B for use in any PLIIM-based system of the present invention. As shown, each optical assembly 380 comprises a PLIA 6A, 6B with a PLIB phase-modulation mechanism 381 realized by a refractive-type

cylindrical lens array ring structure 382 for micro-oscillating the PLIB prior to illuminating the target object. The lens array ring structure 382 can be made from a lenticular screen material having cylindrical lens elements (CLEs) arranged with a high spatial period (e.g. 64 CLEs per inch). The lenticular screen material can be carefully heated to soften the material so that it may be configured in in a ring geometry, and securely held at its bottom end within a groove formed within support ring 382, as shown in Fig. 1I9B. In accordance with the first generalized method, the refractive-type cylindrical lens array ring structure 382 is rotated by a high-speed electric motor 384 about its axis through the PLIB 383 produced by the PLIA 6A, 6B. The function of the rotating cylindrical lens array ring structure 382 is to module the phase along the wavefront of the PLIB and produce numerous substantially different time-varying speckle-noise patterns at the image detection array of the IFD Subsystem during the photo-integration time period thereof, so that the numerous time-varying speckle-noise patterns can be temporally and spatially averaged during the photo-integration time period of the image detection array.

As shown in Fig. 1I9B, the cylindrical lens ring structure 382 comprises a cylindrically-configured array of cylindrical lens 386 mounted perpendicular to the surface of an annulus structure 387, connected to the shaft of electric motor 384 by way of support arms 388A, 388B, 388C and 388D. The cylindrical lenslets should face radiallly outwardly, as shown in Fig. 1I9B. As shown in Fig. 1I9A, the PLIA 6A, 6B is stationarily mounted relative to the rotor of the motor 384 so that the PLIB 383 produced therefrom is oriented substantially perpendicular to the axis of rotation of the motor, and is transmitted through each cylindrical lens element 386 in the ring structure 382 at an angle which is substantially perpendicular to the longitudinal axis of each cylindrical lens element 386. The composite PLIB 389 produced from optical assemblies 380A and 380B is spatially coherent-reduced and yields images having reduced speckle-noise patterns in accordance with the present invention.

In the case of optical system of Fig. 1I9A, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated at the image detection array during each photo-integration time period thereof: (i) the spatial period of the cylindrical lens elements in the lens array ring structure; (ii) the width dimension of each cylindrical lens element; (iii) the circumference of the cylindrical lens array ring structure; (iv) the tangential velocity thereof at the point where the PLIB intersects the transmitted PLIB; and (v) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (1) through (iv) will factor into the specification of the spatial phase modulation function (SPMF) of this speckle-noise reduction subsystem design. In general, if the PLIIM-based system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrolated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Adjustment of the above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at hand.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I9A, the number of substantially different time-varying speckle-noise pattern samples which need to be

generated per each photo-integration time interval of the image detection array can be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this sample number at the image detection array can be expressed mathamatically in terms of (i) the spatial gradient of the spatial phase modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

Apparatus Of The Present Invention For Micro-Oscillating The Planar Laser Illumination (PLIB) Using A Diffractive-Type Cylindrical Lens Array Ring Structure To Spatial Intensity Modulate Said PLIB Prior To Target Object Illumination

In Fig. 1I10A, there is shown a pair of optical assemblies 390A and 390B for use in any PLIIM-based system of the present invention. As shown, each optical assembly 390 comprises a PLIA 6A, 6B with a PLIB phase-modulation mechanism 391 realized by a diffractive (i.e. holographic) type cylindrical lens array ring structure 392 for micro-oscillating the PLIB 393 prior to illuminating the target object. The lens array ring structure 392 can be made from a strip of holohraphic recording material 392A which has cylindrical lenses elements holographically recorded therein using conventional holographic recording techniques. This holographically recorded strip 392A is sandwiched between an inner and outer set of glass cylinders 392B and 392C, and sealed off from air or moisture on its top and bottom edges using a glass sealant. The holographically recorded cylindrical lens elements (CLEs) are arranged about the ring structure with a high spatial period (e.g. 64 CLEs per inch). HDE construction techniques disclosed in copending U.S. Application No. 09/071,512, incorporated herein by reference, can be used to manufacture the HDE ring structure 312. The ring structure 392 is securely held at its bottom end within a groove formed within annulus support structure 397, as shown in Fig. 1I9B. As shown in Fig. 1I10B, the cylindrical lens ring structure 392 is mounted perpendicular to the surface of an annulus structure 397, connected to the shaft of electric motor 394 by way of support arms 398A, 398B, 398C, and 398D. As shown in Fig. 1I10A, the PLIA 6A, 6B is stationarily mounted relative to the rotor of the motor 394 so that the PLIB 393 produced therefrom is oriented substantially perpendicular to the axis of rotation of the motor 394, and is transmitted through each holographically-recorded cylindrical lens element (HDE) 396 in the ring structure 392 at an angle which is substantially perpendicular to the longitudinal axis of each cylindrical lens element 396.

In accordance with the first generalized method, the cylindrical lens array ring structure 392 is rotated by a high-speed electric motor 394 about its axis as the composite PLIB is transmitted from the PLIA 6A through the rotating cylindrical lens array ring structure. During the transmission process, the phase along the wavefront of the PLIB is spatial phase modulated and produces numerous substantially different time-varying speckle-noise patterns at the image detection array of the IFD Subsystem during the photo-integration time period thereof. These time-varying speckle-noise patterns are temporally and spatially averaged at the image detector

during each photo-integration time, thereby reducing the RMS power of speckle-noise patterns observed at the image detection array.

In the case of optical system of Fig. 1I10A, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated at the image detection array during each photo-integration time period thereof: (i) the spatial period of the cylindrical lens elements in the lens array ring structure; (ii) the width dimension of each cylindrical lens element; (iii) the circumference of the cylindricall lens array ring structure; (iv) the tangential velocity thereof at the point where the PLIB intersects the transmitted PLIB; and (v) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (1) through (iv) will factor into the specification of the spatial phase modulation function (SPMF) of this speckle-noise reduction subsystem design. In general, if the PLIIM-based system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrolated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Adjustment of the above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at hand.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I9A, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval of the image detection array can be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this sample number at the image detection array can be expressed mathamatically in terms of (i) the spatial gradient of the spatial phase modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

<u>Apparatus Of The Present Invention For Micro-Oscillating The Planar Laser Illumination (PLIB) Using A Reflective-Type Phase Modulation Disc Structure To Spatial Phase Modulate Said PLIB Prior To Target Object Illumination</u>

In Fig. 1I11A, there is shown a PLIM-based system 400 embodying a pair of optical assemblies 401A and 401B, each comprising a reflective-type phase-modulation mechanism 402 mounted between a pair of PLIAs 6A1 and 6A2, and towards which the PLIAs 6B1 and 6B2 direct a pair of composite PLIBs 402A and 402B. In accordance with the first generalized method, the phase-modulation mechanism 402 comprises a reflective-type PLIB phase-modulation disc structure 404 having a cylindrical surface 405 with randomly or periodically distributed relief (or recessed) surface discontinuities that function as "spatial phase modulation elements". The phase modulation disc 404 is rotated by a high-speed electric motor 407 about its axis so that, prior to illumination of the target object, each PLIB 402A and 402B is reflected off the phase modulation surface of the disc 404 as a composite PLIB 409 (i.e. in a direction of coplanar alignment with the field of view (FOV) of the IFD subsystem), spatial phase modulates

the PLIB and causing the PLIB 409 to be micro-oscillated along its planar extent. This spatial phase-modulation of the PLIB modulates the phase along the wavefront of the transmitted PLIB, and produces numerous substantially different time-varying speckle-noise patterns at the image detection array during each photo-integration time period (i.e. interval) thereof. The time-varying speckle-noise patterns are temporally and spatially averaged at the image detection array during the photo-integration time period thereof, thereby reducing the RMS power of the speckle-noise patterns observe at the image detection array. As shown in Fig. 1I11B , the reflective phase-modulation disc 404, while spatially-modulating the PLIB, does not effect the coplanar relationship maintained between the transmitted PLIB 409 and the field of view (FOV) of the IFD Subsystem.

In the case of optical system of Fig. 1I11A, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated at the image detection array during each photo-integration time period thereof: (i) the spatial period of the spatial phase modulating elements arranged on the surface 405 of each disc structure 404; (ii) the width dimension of each spatial phase modulating element on surface 405; (iii) the circumference of the disc structure 404; (iv) the tangential velocity on surface 405 at which the PLIB reflects thereoff; and (v) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (1) through (iv) will factor into the specification of the spatial phase modulation function (SPMF) of this speckle-noise reduction subsystem design. In general, if the PLIIM-based system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrolated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Adjustment of the above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at hand.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I11A, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval of the image detection array can be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this sample number at the image detection array can be expressed mathamatically in terms of (i) the spatial gradient of the spatial phase modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

Second Generalized Method Of Speckle-Noise Pattern Reduction And Particular Forms Of Apparatus Therefor Based On Reducing The Temporal-Coherence Of The Planar Laser Illumination Beam Before It Illuminates The Target Object

Referring to 1I12 through 1I15C, the second generalized method of speckle-noise pattern reduction and particular forms of apparatus therefor will be described. This generalized method

is based on the principle of temporal intensity modulating the "transmitted" planar laser illumination beam (PLIB) prior to illuminating a target object (e.g. package) therewith so that the object is illuminated with a temporally coherent-reduced planar laser beam and, as a result, numerous substantially different time-varying speckle-noise patterns are produced and detected over the photo-integration time period of the image detection array (in the IFD subsystem), thereby allowing these speckle-noise patterns to be temporally averaged and/or spatially averaged and the observable speckle-noise patterns reduced. This method can be practiced with any of the PLIIM-based systems of the present invention disclosed herein, as well as any system constructed in accordance with the general principles of the present invention.

As illustrated at Block A in Fig. 1I21B, the first step of the fourth generalized method shown in Figs. 1I20 through 1I21A involves modulating the temporal intensity of the transmitted planar laser illumination beam (PLIB) along the planar extent thereof according to a (random or periodic) temporal-intensity modulation function (TIMF) prior to illumination of the target object with the PLIB. This causes the phase along the wavefront of the PLIB to be modulated and numerous substantially different time-varying speckle-noise patterns produced at the image detection array during the photo-integration time period thereof.. As indicated at Block B in Fig. 1I13B, the second step of the method involves temporally and spatially averaging the numerous time-varying speckle-noise patterns detected during each photo-integration time period of the image detection array in the IFD Subsystem, thereby reducing the RMS power of the speckle-noise patterns observed at the image detection array.

When using the second generalized method, the target object is repeatedly illuminated with laser light apparently originating at different moments in time (i.e. from different virtual illumination sources) over the photo-integration period of each detector element in the image detection array of the PLIIM system. As the relative phase delays between these virtual illumination sources are changing over the photo-integration time period of each image detection element, these virtual illumination sources are effectively rendered temporally incoherent (or temporally coherent-reduced) with respect to each other. On a time-average basis, these time-varying speckle-noise patterns are temporally and spatially averaged during the photo-integration time period of the image detection elements, thereby reducing the RMS power of the observed speckle-noise patterns. As speckle-noise patterns are roughly uncorrelated at the image detector, the reduction in speckle noise amplitude should be proportional to the square root of the number of independent real and virtual laser illumination sources contributing to the illumination of the target object and formation of the image frames thereof. As a result of the method of the present invention, image-based bar code symbol decoders and/or OCR processors operating on such digital images can be processed with significant reductions in error.

The second generalized method above can be explained in terms of Fourier Transform optics. When temporally modulating the transmitted PLIB by a periodic or random temporal intensity modulation (TIMF) function, while satisfying conditions (i) and (ii) above, a temporal intensity modulation process occurs on the time domain. This temporal intensity modulation process is equivalent to mathematically multiplying the transmitted PLIB by the temporal intensity

modulation function. This multiplication process on the time domain is equivalent on the time-frequency domain to the convolution of the Fourier Transform of the temporal intensity modulation function with the Fourier Transform of the transmitted PLIB. On the time-frequency domain, this convolution process generates temporally-incoherent (i.e. statistically-uncorrelated) spectral components which are permitted to spatially-overlap at each detection element of the image detection array (i.e. on the spatial domain) and produce time-varying speckle-noise patterns which are temporally and spatially averaged during the photo-integration time period of each detector element, to reduce the RMS power of speckle-noise patterns observed at the image detection array.

In general, various types of temporal intensity modulation techniques can be used to carry out the first generalized method including, for example: mode-locked laser diodes (MLLDs) employed in the planar laser illumination array; electrically-passive optically resonant cavities affixed external to the VLD; electro-optical temporal intensity modulators disposed along the optical path of the composite planar laser illumination beam; laser beam frequency-hopping devices; internal and external type laser beam frequency modulation (FM) devices; internal and external laser beam amplitude modulation (AM) devices; etc. Several of these temporal intensity modulation mechanisms will be described in detail below.

<u>Electro-Optical Apparatus Of The Present Invention For Temporal Intensity Modulating The Planar Laser Illumination Beam Prior To Target Object Illumination Employing High-Speed Beam Gating/Switching Principles</u>

In Figs. 1I14A through 1I14B, there is shown an optical assembly 420 for use in any PLIIM-based system of the present invention. As shown, the optical assembly 420 comprises a PLIA 6A, 6B with a refractive-type cylindrical lens array 421 (e.g. operating according to refractive, diffractive and/or reflective principles) supported in frame 822, and an electrically-active temporal intensity modulation panel 423 (e.g. high-speed electro-optical gating/switching device) arranged in front of the cylindrical lens array 421. Electronic driver circuitry 424 is provided to drive the temporal intensity modulation panel 43 under the control of camera control computer 22. In the illustrative embodiment, electronic driver circuitry 424 can be programmed to produce an output PLIB 425 consisting of a periodic light pulse train, wherein each light pulse has an ultra-short time duration and a rate of repetition (i.e. temporal characteristics) which generate spectral harmonics on the time-frequency domain that result in the generation of numerous time-varying speckle-patterns during each photo-integration time period of the image detection array in the PLIIM-based system.

During system operation, the PLIB 424 is temporal intensity modulated according to a (random or periodic) temporal-intensity modulation (e.g. windowing) function (TIMF) so that the phase along the wavefront of the PLIB is modulated and numerous substantially different time-varying speckle-noise patterns produced at the image detection array during the photo-integration time period thereof. The time-varying speckle-noise patterns detected at the image

detection array are temporally and spatially averaged during each photo-integration time period thereof, thus reducing the RMS power of the speckle-noise patterns observed at the image detection array.

In the case of optical system of Fig. 1I14A, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated during each photo-integration time period: (i) the time duration of each light pulse in the output PLIB 425; (ii) the rate of repetition of the light pulses in the output PLIB; and (iii) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (1) and (ii) will factor into the specification of the temporal intensity modulation function (TIMF) of this speckle-noise reduction subsystem design. In general, if the PLIIM-based system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrolated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Adjustment of the above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at hand.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I14A, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval of the image detection array can be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this sample number at the image detection array can be expressed mathamatically in terms of (i) the temporal derivative of the temporal intensity modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

<u>Electrically-Passive Optical Apparatus Of The Present Invention For Temporal-Intensity Modulating The Planar Laser Illumination Beam Prior To Target Object Illumination Employing Photon Trapping, Delaying And Releasing Principles Within An Optically Resonant Cavity Affixed To Each Visible Laser Diode Within The Planar Laser Illumination Array</u>

In Figs. 1I15A through 1I15B, there is shown an optical assembly 430 for use in any PLIIM-based system of the present invention. As shown, the optical assembly 430 comprises a PLIA 6A, 6B with a refractive-type cylindrical lens array 431 (e.g. operating according to refractive, diffractive and/or reflective principles) supported within frame 432, and an electrically-passive temporal intensity modulation (etelon) device 433 (e.g. an external optically resonant cavity) affixed to each VLD 13 of the PLIA 6A, 6B.

The primary principle of this temporal-intensity modulation technique is to delay a portion of the laser light emitted by each laser diode 13 by a time longer than the inherent temporal coherence length of the laser diode. In this embodiment, this is achieved by employing photon trapping, delaying and releasing principles within an optically resonant cavity. Typical laser diodes have a coherence length of a few centimeters (cm). Thus, if some of the laser

illumination can be delayed by the time of flight of a few cm, then it will be incoherent with the original laser illumination. The electrically-passive device 433 shown in Fig. 1I15B can be realized by a pair of parallel, reflective surfaces (e.g. plates, films or layers) 436A and 436B, mounted to the output of each VLD 13 in the PLIA 6A, 6B. If one surface is essentially totally reflective (e.g. 97% reflective) and the other about 94% reflective, then about 3% of the laser illumination (i.e. photons) will escape the device through the partially reflective surface of the device on each round trip. The laser illumination will be delayed by the time of flight for one round trip between the plates. If the plates 436A and 436B are separated by a space 437 of several centimeters length, then this delay will be greater than the coherence time of the laser source. In the illustrative embodiment of Figs. 1I15A and 1I15B, the emitted light (i.e. photons) will make about thirty (30) trips between the plates. This has the effect of mixing thirty (30) photon distribution samples from the laser source, each sample residing outside the coherence time thereof, thus destroying or substantially reducing the temporal coherence of the laser illumination sources in the PLIA of the present invention. A primary advantage of this technique is that it employs electrically-passive components which might be manufactured relatively inexpensively in a mass-production environment. Suitable components for constructing such electrically-passive temporal intensity modulation devices 433 can be obtained from various commercial vendors.

During operation, the transmitted PLIB 434 is temporal intensity modulated according to a (random or periodic) temporal-intensity modulation (e.g. windowing) function (TIMF) so that the phase along the wavefront of the PLIB is modulated and numerous substantially different time-varying speckle-noise patterns are produced at the image detection array during the photo-integration time period thereof. The time-varying speckle-noise patterns detected at the image detection array are temporally and spatially averaged during each photo-integration time period thereof, thus reducing the RMS power of the speckle-noise patterns observed at the image detection array.

In the case of optical system of Fig. 1I15A, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated during each photo-integration time period: (i) the spacing between reflective surfaces (e.g. plates, films or layers) 436A and 436B; (ii) the reflection coefficients of these reflective surfaces; and (iii) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (1) and (ii) will factor into the specification of the temporal intensity modulation function (TIMF) of this speckle-noise reduction subsystem design. In general, if the PLIIM-based system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrolated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Adjustment of the above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at hand.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I15A, the number of substantially different time-varying speckle-noise pattern samples which need to be

generated per each photo-integration time interval can be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this sample number at the image detection array can be expressed mathamatically in terms of (i) the temporal derivative of the temporal intensity modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

Electro-Optical Apparatus Of The Present Invention For Temporal Intensity Modulating The Planar Laser Illumination Beam Prior To Target Object Illumination Employing Visible Mode-Locked Laser Diodes (MLLDs)

In Figs. 1I15C through 1I15D, there is shown an optical assembly 440 for use in any PLIIM-based system of the present invention. As shown, the optical assembly 440 comprises a cylindrical lens array 441 (e.g. operating according to refractive, diffractive and/or reflective principles), mounted in front of a PLIA 6A, 6B embodying a plurality of visible mode-locked visible diodes (MLLDs) 13'. In accordance with the second generalized method of the present invention, each visible MLLD 13' is configured and tuned to produce ultra-short pulses of light at a frequency which (i) results in a transmitted PLIB 443 that is temporal-intensity modulated according to a (random or periodic) temporal-intensity modulation function (TIMF) which causes, on average, differences in phase along the wavefront of the transmitted PLIB (i.e. on the order of 1/2 of the laser illumination wavelength) enabling one cycle of speckle-noise pattern variation to occur at image detection array of the IFD Subsystem during each optical period of the visible illumination source, and (ii) the rate of temporal-intensity modulation is greater than or equal to the inverse of the photo-integration time period of the image detection array in the IFD Subsystem enabling temporal and/or spatial averaging of the time-varying speckle-noise patterns detected by the image detection array during the photo-integration time period of the image detection array.

As shown in Fig. 1I15D, each MLLD 13' employed in the PLIA of Fig. 1I15C comprises: a multi-mode laser diode cavity 444 referred to as the active layer (e.g. InGaAsP) having a wide emission-bandwidth over the visible band, and suitable time-bandwidth product for the application at hand; a collimating lenslet 445 having a very short focal length; an active mode-locker 446 (e.g. temporal-intensity modulator) operated under switched electronic control of a TIM controller 447; a passive-mode locker (i.e. saturable absorber) 448 for controlling the pulse-width of the output laser beam; and a mirror 449, affixed to the passive-mode locker 447, having 99% reflectivity and 1% transmittivity at the operative wavelength band of the visible MLLD. The multi-mode diode laser diode 13' generates (within its primary laser cavity) numerous modes of oscillation at different optical wavelengths within the time-bandwidth product of the cavity. The collimating lenslet 445 collimates the divergent laser output from the diode cavity 444, has a very short local length and defines the aperture of the optical system. The collimated output from the lenslet 445 is directed through the active mode locker 446,

disposed at a very short distance away (e.g. 1 millimeter). The active mode locker 446 is typically realized as a high-speed temporal intensity modulator which is electronically-switched between optically transmissive and optically opaque states at a switching frequency equal to the frequency (f_{MLB}) of the mode-locked laser beam pulses to be produced at the output of each MLLD. This laser beam pulse frequency f_{MLB} is governed by the following equation: $f_{MLB}= c/2L$, where c is the speed of light, and L is the total length of the MLLD, as defined in Fig. 1I15D. The partially transmission mirror 449, disposed a short distance (e.g. 1 millimeter) away from the active mode locker 446, is characterized by a reflectivity of about 99%, and a transmittance of about 1% at the operative wavelength band of the MLLD. The passive mode locker 448, applied to the interior surface of the mirror 449, is a photo-bleachable saturatable material which absorbs photons at the operative wavelength band. When the passive mode blocker 448 is totally absorbed (i.e. saturated), it automatically transmits the absorbed photons as a burst (i.e. pulse) of output laser light from the visible MLLD. After the burst of photons are emitted, the passive mode blocker 448 quickly recovers for the next photon absorption/saturation/release cycle. Notably, absorption and recovery time characteristics of the passive mode blocker 448 controls the time duration (i.e. width) of the optical pulses produced from the visible MLLD. In typical high-speed package scanning applications requiring relatively short photo-integration time period (e.g. 10^{-4} sec) the absorption and recovery time characteristics of the passive mode blocker 448 will be on the order of femtoseconds, to ensure that the composite PLIB 443 produced from the MLLD-based PLIA contains higher order spectral harmonics (i.e. components) with sufficient magnitude to cause a significant reduction in temporal coherence of the PLIB and thus in the power-density spectrum of the speckle-noise pattern observed at the image detection array of the IFD Subsystem. For further details regarding the construction of MLLDs, reference should be made to "Diode Laser Arrays" (1994), by D. Botez and D.R. Scifres, supra, incorporated herein by reference.

<u>Other Techniques For Reducing Speckle-Noise Patterns By Temporal Intensity Modulating Planar Laser Illumination Beams (PLIBs) According To The Present Invention</u>

There are other techniques for reducing speckle-noise patterns by temporal intensity modulating PLIBs produced by PLIAs according to the principles of the present invention. A straightforward approach to temporal intensity modulating the PLIB would be to either (i) modulate the diode current driving the VLDs of the PLIA in a non-linear mode of operation, or (ii) use an external optical modulator to temporal intensity modulate the PLIB in a non-linear mode of operation. By operating VLDs in a non-linear manner, high order spectral harmonics can be produced which, in cooperation with a cylindrical lens array, cooperate to generate substantially different time-varying speckle-noise patterns during each photo-integration time period of the image detection array of the PLIIM-based system.

In principal, non-linear amplitude modulation (AM) techniques can be employed with the first approach (i) above, whereas the non-linear AM, frequency modulation (FM), or temporal

phase modulation (PM) techniques can be employed with the second approach (ii) above. The primary purpose of applying such non-linear laser modulation techniques is to introduce spectral side-bands into the optical spectrum of the planar laser illumination beam (PLIB). The spectral harmonics in this side-band spectra are determined by the sum and difference frequencies of the optical carrier frequency and the modulation frequency employed. If the PLIB is temporal intensity modulated by a periodic temporal intensity modulation (time-windowing) function (e.g. 100% AM), and the time period of this time windowing function is sufficiently high, then two points on the target surface will be illuminated by light of different optical frequencies (i.e. uncorrelated virtual laser illumination sources) carried within pulsed-periodic PLIB. In general, if the difference in optical frequencies in the pulsed-periodic PLIB is large (i.e. caused by compressing the time duration of its constituent light pulses) compared to the inverse of the photo-integration time period of the image detection array, then observed the speckle-noise pattern will appear to be washed out (i.e. additively cancelled) by the beating of the two optical frequencies at the image detection array. To ensure that the uncorrelated speckle-noise patterns detected at the image detection array can additively average (i.e. cancel) out, the rate of light pulse repetition in the transmitted PLIB should be greater than or equal to the inverse of the photo-integration time period of the image detector array (i.e. $1/\Delta T_{\text{photo-integration}}$), and the time duration of each light pulse in the pulsed PLIB should be compressed to impart greater magnitude to the higher order spectral harmonics comprising the periodic-pulsed PLIB generated by such non-linear modulation techniques.

Notably, both external-type and internal-type laser modulation devices can be used to generate higher order spectral harmonics within transmitted PLIBs. Internal-type laser modulation devices, employing laser current and/or temperture control techniques, modulate the temporal intensity of the transmitted PLIB in a non-linear manner (i.e. zero PLIB power, full PLIB power) by controlling the current of the VLDs producing the PLIB. In contrast, external-type laser modulation devices, employing high-speed optical-gating and other light control devices, modulate the temporal intensity of the transmitted PLIB in a non-linear manner (i.e. zero PLIB power, full PLIB power) by directly controlling temporal intensity of luminous power in the transmitted PLIB. Typically, such external-type techniques will require additional heat management apparatus. Cost and spatial constraints will factor in which techiques to use in a particular application.

<u>Electro-Optical Apparatus Of The Present Invention For Temporal-Intensity Modulating The Planar Laser Illumination Beam Prior To Target Object Illumination Employing Drive-Current Modulated Visible Laser Diodes (VLDs)</u>

In Figs. 1I16A and 1I16B, there is shown an optical assembly 450 for use in any PLIIM-based system of the present invention. As shown, the optical assembly 450 comprises a stationary cylindrical lens array 451 (e.g. operating according to refractive, diffractive and/or reflective principles), supported in a frame 452 and mounted in front of a PLIA 6A, 6B

embodying a plurality of drive-current modulated visible laser diodes (VLDs) 13. In accordance with the second generalized method of the present invention, each VLD 13 is driven in a non-linear manner by an electrical time-varying current produced by a high-speed VLD drive current modulation circuit 454, In the illustrative embodiment, the VLD drive current modulation circuit 454 is supplied with DC power from a DC power source 403 and operated under the control of camera control pattern 22. The VLD drive current supplied to each VLD effectively modulates the amplitude of the output laser beam 456. Preferably, the depth of amplitude modulation (AM) of each output laser beam will be close to 100% in order to increase the magnitude of the higher order spectral harmonics generated during the AM process. As mentioned above, increasing the rate of change of the amplitude modulation of the laser beam will result in higher order optical components in the composite PLIB.

In alternative embodiments, the high-speed VLD drive current modulation circuit 454 can be operated (under the control of camera control computer 22 or other programmed microprocessor) so that the VLD drive currents generated by VLD drive current modulation circuit 454 periodically induce "spectral mode-hopping" within each VLD numerous time during each photo-integration time interval of the PLIIM-based system. This will cause each VLD to generate multiple spectral components within each photo-integration time period of the image detection array.

Optionally, the optical assembly 450 may further comprise a VLD temperature controller 456, operably connected to the camera controller 22, and a plurality of temperature control elements 457 mounted to each VLD. The function of the temperature controller 456 is to control the junction temperature of each VLD. The camera control computer 22 can be programmed to control both VLD junction temperature and junction current so that each VLD is induced into modes of spectral hopping for a maximal percentage of time (during the photo-integration time period of the image detector. The result of such spectral mode frequency should be to cause temporal intesity modulation of the transmitted PLIB 458, thereby enabling the generation of numerous time-varying speckle-noise patterns, and the temporal and spatial averaging thereof to reduce the RMS power of speckle-noise patterns observed at the image detection array.

Third Generalized Method Of Speckle-Noise Pattern Reduction And Particular Forms Of Apparatus Therefor Based On Reducing The Spatial-Coherence Of The Planar Laser Illumination Beam Before It Illuminates The Target Object

Referring to Figs. 1I17 through 1I19D, the third generalized method of speckle-noise pattern reduction and particular forms of apparatus therefor will be described. This generalized method is based on the principle of spatially modulating the "transmitted" planar laser illumination beam (PLIB) prior to illuminating a target object therewith so that the object is illuminated with a spatially coherent-reduced planar laser beam and, as a result, numerous time-varying (random) speckle-noise patterns are produced and detected over the photo-integration

time period of the image detection array (in the IFD subsystem), thereby allowing these speckle-noise patterns to be temporally averaged and/or spatially averaged and the observable speckle-noise pattern reduced. This method can be practiced with any of the PLIM-based systems of the present invention disclosed herein, as well as any system constructed in accordance with the general principles of the present invention.

As illustrated at Block A in Fig. 1I18B, the first step of the third generalized method shown in Figs. 1I7 through 1I19D involves spatial intensity modulating the transmitted PLIB along the planar extent thereof according to a (random or periodic) spatial intensity modulation (i.e. windowing) function (SIMF) prior to illumination of the target object with the PLIB, so as to modulate the phase along the wavefront of the PLIB and produce numerous substantially different time-varying speckle-noise pattern at the image detection array of the IFD Subsystem during the photo-integration time period thereof. As indicated at Block B in Fig. 1I18B, the second step of the method involves temporally and spatially averaging the numerous substantially different speckle-noise patterns produced at the image detection array during the photo-integration time period thereof, thereby reducing the RMS power of speckle-noise patterns observed at the image detection array.

When using the third generalized method, the target object is repeatedly illuminated with laser light apparently originating from different points (i.e. virtual illumination sources) in space over the photo-integration period of each detector element in the linear image detection array of the PLIIM system, during which reflected laser illumination is received at the detector element. As the relative phase delays between these virtual illumination sources are changing over the photo-integration time period of each image detection element, these virtual sources are effectively rendered spatially incoherent with each other. On a time-average basis, these time-varying speckle-noise patterns can be temporally and spatially averaged during the photo-integration time period of the image detection elements, thereby reducing the RMS power of speckle-noise patterns observed thereat. As speckle-noise patterns are roughly uncorrelated at the image detection array, the reduction in speckle-noise power should be proportional to the square root of the number of independent virtual laser illumination sources contributing to the illumination of the target object and formation of the images frame thereof. As a result of the present invention, image-based bar code symbol decoders and/or OCR processors operating on such digital images can be processed with significant reductions in error.

The third generalized method above can be explained in terms of Fourier Transform optics. When spatial-intensity modulating the transmitted PLIB by a periodic or random spatial intensity modulation function (SIMF), while satisfying conditions (i) and (ii) above, a spatial intensity modulation process occurs on the spatial domain. This spatial modulation process is equivalent to mathematically multiplying the transmitted PLIB by the spatial modulation function. This multiplication process on the spatial domain is equivalent on the spatial-frequency domain to the convolution of the Fourier Transform of the spatial intensity modulation function with the Fourier Transform of the composite PLIB. On the spatial-frequency domain, this convolution process generates spatially-incoherent (i.e. statistically-uncorrelated) spectral

components which are permitted to spatially-overlap at each detection element of the image detection array (i.e. on the spatial domain) and produce time-varying speckle-noise patterns which are temporally and spatially averaged during the photo-integration time period of each detector element, to reduce the speckle-noise pattern observed at the image detection array.

In general, various types of spatial light modulation techniques can be used to carry out the third generalized method including, for example: a mechanism for physically or photo-electronically rotating a spatial intensity modulator (e.g. apertures, irises, Fourier Transform plates, etc.) about the optical axis of the imaging lens of the camera module; and any other axially symmetric, rotating spatial intensity modulation element arranged before the entrance pupil of the camera module, through which the received PLIB beam may enter at any angle or orientation during illumination and image detection operations. Several of these spatial intensity modulation mechanisms will be described in detail below.

Apparatus Of The Present Invention For Micro-Oscillating A Pair Of Spatial Intensity Modulation (SIM) Panels With Respect To The Cylindrical Lens Arrays So As To Spatial-Intensity Modulate The Planar Laser Illumination Beam Prior To Target Object Illumination

In Figs. 1I19 through 1I9D, there is shown an optical assembly 730 for use in any PLIIM-based system of the present invention. As shown, the optical assembly 730 comprises a PLIA 6A with a pair of spatial intensity modulation (SIM) panels 731A and 731B, and an electronically-controlled mechanism 732 for micro-oscillating SIM panels 731A and 731B, behind a cylindrical lens array 733 mounted within a support frame 734 with the SIM panels. Each SIM panel comprises an array of light intensity modifying elements 735, each having a different light transmitivity value (e.g. measured against a grey-scale) to impart a different degree of intensity modulation along the wavefront of the composite PLIB 738 transmitted through the SIM panels. The width dimensions of each SIM element 735, and their spatial periodicity, may be determined by the spatial intensity modulation requirements of the application at hand. In some embodiments, the width of each SIM element 735 may be random, and aperiodically arranged along the linear extent of each SIM panel. In other embodiments, the width of the SIM elements may be similar and periodically arranged along each SIM panel. As shown in Fig. 1I19C, support frame 734 has a light transmission window 740, and mounts the SIM panels 731A and 731B in a relative reciprocating manner, behind the cylindrical lens array 733, and two pairs of ultrasonic (or other motion) transducers 736A, 736B, and 737A, 737B arranged (90 degrees out of phase) in a push-pull configuration, as shown in Fig. 1I19D.

In accordance with the first generalized method, the SIM panels 731A and 731B are micro-oscillated, relative to each other (out of phase by 90 degrees) using motion transducers 736A, 736B, and 737A, 737B. During operation of the mechanism, the individual beam components within the composite PLIB 738 are transmitted through the reciprocating SIM panels 731A and 731B, and micro-oscillated (i.e. moved) along the planar extent thereof by an amount of distance Δx or greater at a velocity $v(t)$ which causes the phase along the wavefronts

of the transmitted PLIB 739 to be modulated and numerous substantially different time-varying speckle-noise patterns generated at the image detection array of the PLIIM-based during the photo-integration time period thereof. The time-varying speckle-noise patterns produced at the image detection array are temporally and spatially averaged during the photo-integration time period thereof, thereby reducing the RMS power of speckle-noise patterns observed at the image detection array.

In the case of optical system of Fig. 1I19A, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated at the image detection array during each photo-integration time period thereof: (i) the spatial frequency and light transmittance values of the SIM panels 731A, 731B; (ii) the length of the cylindrical lens array733 and the SIM panels; (iii) the relative velocities thereof; and (iv) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. In general, if a system requires an increase in reduction in speckle-noise at the image detection array, then the system must generate more uncorrolated time-varying speckle-noise patterns for averaging over each photo-integration time period of the image detection array employed in the system. Parameters (1) through (iii) will factor into the specification of the spatial phase modulation function (SPMF) of this speckle-noise reduction subsystem design. In general, if the system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrolated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Adjustment of the above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at hand.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I19A, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval of the image detection array can be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this sample number at the image detection array can be expressed mathamatically in terms of (i) the spatial gradient of the spatial phase modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

<u>Fourth Generalized Method Of Speckle-Noise Pattern Reduction And Particular Forms Of Apparatus Therefor Based On Reducing The Spatial-Coherence Of The Planar Laser Illumination Beam After It Illuminates The Target</u>

Referring to Figs. 1I20 through 1I22B, the fourth generalized method of speckle-noise pattern reduction and particular forms of apparatus therefor will be described. This generalized method is based on the principle of spatial-intensity modulating the composite-type "return" PLIB produced when the transmitted PLIB illuminates and reflects and/or scatters off the target object. The return PLIB constitutes a spatially coherent-reduced laser beam and, as a result,

numerous time-varying speckle-noise patterns are detected over the photo-integration time period of the image detection array in the IFD subsystem, thereby allowing these time-varying speckle-noise patterns to be temporally and/or spatially averaged and the observable speckle-noise pattern reduced. This method can be practiced with any of the PLIM-based systems of the present invention disclosed herein, as well as any system constructed in accordance with the general principles of the present invention.

As illustrated at Block A in Fig. 1I18B, the first step of the third generalized method shown in Figs. 1I17 through 1I18A involves spatially modulating the received PLIB along the planar extent thereof according to a (random or periodic) spatial-intensity modulation function (SIMF) after illuminating the target object with the PLIB, so as to modulate the phase along the wavefront of the received PLIB and produce numerous substantially different time-varying speckle-noise patterns during each photo-integration time period of the image detection array of the PLIIM-based system. As indicated at Block B in Fig. 1I18B, the second step of the method involves temporally and spatially averaging these time-varying speckle-noise patterns during the photo-integration time period of the image detection array, thus reducing the RMS power of speckle-noise patterns observed at the image detection array.

When using the third generalized method, the image detection array in the PLIIM-based system repeatedly detects laser light apparently originating from different points in space (i.e. from different virtual illumination sources) over the photo-integration period of each detector element in the image detection array. As the relative phase delays between these virtual illumination sources are changing over the photo-integration time period of each image detection element, these virtual sources are effectively rendered spatially incoherent (or spatially coherent-reduced) with respect to each other. On a time-average basis, these time-varying speckle-noise patterns are temporally and spatially averaged during the photo-integration time period of the image detection array, thereby reducing the RMS power of speckle-noise patterns observed thereat. As speckle noise patterns are roughly uncorrelated at the image detector, the reduction in speckle-noise power should be proportional to the square root of the number of independent real and virtual laser illumination sources contributing to formation of the image frames of the target object. As a result of the present invention, image-based bar code symbol decoders and/or OCR processors operating on such digital images can be processed with significant reductions in error.

The third generalized method above can be explained in terms of Fourier Transform optics. When spatially modulating a return PLIB by a periodic or random spatial modulation (i.e. windowing) function, while satisfying conditions (i) and (ii) above, a spatial modulation process occurs on the spatial domain. This spatial modulation process is equivalent to mathematically multiplying the composite return PLIB by the spatial modulation function. This multiplication process on the spatial domain is equivalent on the spatial-frequency domain to the convolution of the Fourier Transform of the spatial modulation function with the Fourier Transform of the return PLIB. On the spatial-frequency domain, this equivalent convolution process generates spatially-incoherent (i.e. statistically-uncorrelated) spectral components which are permitted to spatially-overlap at each detection element of the image detection array (i.e. on the spatial

domain) and produce time-varying speckle-noise patterns which are temporally and spatially averaged during the photo-integration time period of each detector element, to reduce the power of speckle-noise patterns observed at the image detection array.

In general, various types of spatial light modulation techniques can be used to carry out the third generalized method including, for example: high-speed electro-optical (e.g. ferro-electric, LCD, etc.) shutters located before the image detector along the optical axis of the camera subsystem; and any other temporal intensity modulation element arranged before the image detector along the optical axis of the camera subsystem, and through which the received PLIB beam may pass during illumination and image detection operations. Several of these temporal intensity modulation mechanisms will be described in detail below.

Apparatus Of The Present Invention For Spatial-Intensity Modulating The Return Planar Laser Illumination Beam Prior To Detection At The Image Detector

In Figs. 1I22A, there is shown an first optical assembly 460 for use at the IFD Subsystem in any PLIIM-based system of the present invention. As shown, the optical assembly 460 comprises an electro-optical mechanism 460 mounted before the pupil of the IFD Subsystem for the purpose of generating a rotating a spatial intensity modulation structure (e.g. maltese-cross aperture) 461, so that the return PLIB 462 is spatial intensity modulated at the IFD subsystem in accordance with the principles of the present invention. The electro-optical mechanism 460 can be realized using a high-speed liquid crystal (LC) spatial intensity modulation panel 463 which is driven by a LCD driver circuit 464 so as to realize a maltese-cross aperture (or other spatial intensity modulation structure) before the camera pupil that rotates about the optical axis of the IFD subsystem during object illumination and imaging operations. Preferably, the angular velocity of the maltese-cross aperture 461 will be sufficient to achieve the spatial intensity modulation function (SIMF) required for speckle-noise pattern reduction in accordance with the principles of the present invention.

In Figs. 1I22B, there is shown a second optical assembly 470 for use at the IFD Subsystem in any PLIIM-based system of the present invention. As shown, the optical assembly 470 comprises an electro-mechanical mechanism 471 mounted before the pupil of the IFD Subsystem for the purpose of generating a rotating maltese-cross aperture 472, so that the return PLIB 473 is spatial-intensity modulated at the IFD subsystem in accordance with the principles of the present invention. The electro-mechanical mechanism 471 can be realized using a high-speed electric motor 474, with appropriate gearing 475, and a rotatable maltese-cross aperture stop 476 mounted within a support mount 477. As a motor drive circuit 478 supplies electrical power to the electrical motor 474, the motor shaft rotates, turning the gearing 475, and thus the maltese-cross aperture stop 476 about the optical axis of the IFD subsystem. Preferably, the maltese-cross aperture 476 will be driven to an angular velocity which is sufficient to achieve the spatial intensity modulation function required for speckle-noise pattern reduction in accordance with the principles of the present invention.

In the case of the optical systems of Figs. 1I22A and 1I22B, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated at the image detection array during each photo-integration time period thereof: (i) the spatial dimensions and relative physical position of the apertures used to form the spatial intensity modulation structure 461, 472; (ii) the angular velocity of the apertures in the rotating structures; and (iii) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (1) through (ii) will factor into the specification of the spatial phase modulation function (SPMF) of this speckle-noise reduction subsystem design. In general, if the PLIIM-based system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrolated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Adjustment of the above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at hand.

For a desired reduction in speckle-noise pattern power in the systems of Figs. 1I22A and 1I22B, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval of the image detection array can be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this sample number at the image detection array can be expressed mathamatically in terms of (i) the spatial gradient of the spatial phase modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

<u>Fifth Generalized Method Of Speckle-Noise Pattern Reduction And Particular Forms Of Apparatus Therefor Based On Reducing The Spatial-Coherence Of The Planar Laser Illumination Beam After It Illuminates The Target</u>

Referring to 1I23 through 1I25, the fifth generalized method of speckle-noise pattern reduction and particular forms of apparatus therefor will be described. This generalized method is based on the principle of temporal intensity modulating the composite-type "return" PLIB produced when the transmitted PLIB illuminates and reflects and/or scatters off the target object. The return PLIB constitutes a temporally coherent-reduced laser beam and, as a result, numerous time-varying (random) speckle-noise patterns are detected over the photo-integration time period of the image detection array (in the IFD subsystem), thereby allowing these time-varying speckle-noise patterns to be temporally and/or spatially averaged and the observable speckle-noise pattern reduced. This method can be practiced with any of the PLIM-based systems of the present invention disclosed herein, as well as any system constructed in accordance with the general principles of the present invention.

As illustrated at Block A in Fig. 1I24B, the first step of the fourth generalized method shown in Figs. 1I20 and 1I21A involves temporal intensity modulating the received PLIB along the planar extent thereof according to a (random or periodic) spatial-intensity modulation (i.e.

windowing) function (TIMF) after illuminating the target object with the PLIB, so as to cause, on average, differences in phase along the wavefront of the PLIB (i.e. on the order of 1/2 of the laser illumination wavelength), enabling one cycle of speckle-noise pattern variation to occur at the image detection array of the IFD Subsystem during the photo-integration time period of the image detection array of the IFD (i.e. camera) subsystem. As indicated at Block B in Fig. 1I21B, the second step of the method involves maintaining the frequency of change of spatial-intensity modulation of the received PLIB to be greater than or equal to the inverse of the photo-integration time period of the image detection array in the IFD Subsystem. This step satisfies enabling temporal and/or spatial averaging of the time-varying speckle-noise patterns detected by the image detection array during the photo-integration time period of the image detection array.

When using the fourth generalized method, the image detector of the IFD subsystem repeatedly detects laser light apparently originating from different moments in space (i.e. virtual illumination sources) over the photo-integration period of each detector element in the image detection array of the PLIIM system. As the relative phase delays between these virtual illumination sources are changing over the photo-integration time period of each image detection element, these virtual sources are effectively rendered temporally incoherent with each other. On a time-average basis, these time-varying speckle-noise patterns can be temporally and spatially averaged during the photo-integration time period of the image detection elements, thereby reducing the speckle-noise pattern (i.e. level) observed thereat. As speckle noise patterns are roughly uncorrelated at the image detector, the reduction in speckle-noise power should be proportional to the square root of the number of independent real and virtual laser illumination sources contributing to formation of the image frames of the target object. As a result of the present invention, image-based bar code symbol decoders and/or OCR processors operating on such digital images can be processed with significant reductions in error.

In general, various types of temporal intensity modulation techniques can be used to carry out the method including, for example: high-speed temporal modulators such as electro-optical shutters, pupils, and stops, located along the optical path of the composite return PLIB focused by the IFD subsystem; etc.

<u>Electro-Optical Apparatus Of The Present Invention For Temporal Intensity Modulating The Planar Laser Illumination Beam Prior To Detecting Images By Employing High-Speed Light Gating/Switching Principles</u>

In Fig. 1I25, there is shown an optical assembly 480 for use in any PLIIM-based system of the present invention. As shown, the optical assembly 480 comprises a high-speed electro-optical temporal intensity modulation panel (e.g. high-speed electro-optical gating/switching panel) 481, mounted along the optical axis of the IFD Subsystem, before the imaging optics thereof. A suitable high-speed temporal intensity modulation panel 481 for use in carrying out this particular embodiment of the present invention might be made using liquid crystal, ferro-

electric or other high-speed light control technology. During operation, the received PLIB is temporal intensity modulated as it is transmitted through the temporal intensity modulation panel 481. During temporal intensity modulation, the phase along the received PLIB is modulated and numerous substantially different time-varying speckle-noise patterns are produced, for temporal and spatial averaging at the image detection array 3A during each photo-integration time period thereof, thereby reducing the RMS power of speckle-noise patterns observed at the image detection array.

The time characteristics of the temporal intensity modulation function (TIMF) created by the temporal intensity modulation panel 481 will be selected in accordance with the principles of the present invention. Preferably, the time duration of the light transmission window of the TIMF will be relatively short, and repeated at a relatively high rate with repect to the inverse of the photo-integration time periond of the image detector so that many spectral-harmonics will be generated each such time period, producing many time-varying speckle-noise patterns at the image detection array. Thus, if a particular imaging application at hand requires a very short photo-integration time period, then it is understood that the rate of repetition of the light transmission window of the TIMP (and thus the rate of switching/gating electro-optical panel 481) will necessarily become higher in order to generate sufficiently weighted spectral components on the time-frequency domain required to reduce the temporal coherence of the received PLIB falling incident at the image detection array.

In the case of the optical system of Fig. 1I25, the following parameters will influence the number of substantially different time-varying speckle-noise patterns generated at the image detection array during each photo-integration time period thereof: (i) the time duration of the light transmission window of the TIMF realized by temporal intensity modulation panel 481; (ii) the rate of repetition of the light duration window of the TIMF; and (iii) the number of real laser illumination sources employed in each planar laser illumination array in the PLIIM-based system. Parameters (1) through (ii) will factor into the specification of the TIMF of this speckle-noise reduction subsystem design. In general, if the PLIIM-based system requires an increase in reduction in the RMS power of speckle-noise at its image detection array, then the system must generate more uncorrolated time-varying speckle-noise patterns for averaging over each photo-integration time period thereof. Adjustment of the above-described parameters should enable the designer to achieve the degree of speckle-noise power reduction desired in the application at hand.

For a desired reduction in speckle-noise pattern power in the system of Fig. 1I25, the number of substantially different time-varying speckle-noise pattern samples which need to be generated per each photo-integration time interval of the image detection array can be experimentally determined without undue experimentation. However, for a particular degree of speckle-noise power reduction, it is expected that the lower threshold for this sample number at the image detection array can be expressed mathamatically in terms of (i) the spatial gradient of the spatial phase modulated PLIB, and (ii) the photo-integration time period of the image detection array of the PLIIM-based system.

While the speckle-noise pattern reduction (i.e. despeckling) techniques described above have been described in conjunction with the system of Fig. 1A for purposes of illustration, it is understood that that any of these techniques can be used in conjunction with any of the PLIIM-based systems of the present invention, and are hereby embodied therein by reference thereto as if fully explained in conjunction with its structure, function and operation.

Second Alternative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 1A

In Fig. 1Q1, the second illustrative embodiment of the PLIIM system of Figs. 1A is shown comprising: a 1-D type image formation and detection (IFD) module 3', as shown in Fig. 1B1; and a pair of planar laser illumination arrays 6A and 6B . As shown, these arrays 6A and 6B are arranged in relation to the image formation and detection module 3 so that the field of view thereof is oriented in a direction that is coplanar with the planes of laser illumination produced by the planar illumination arrays, without using any laser beam or field of view folding mirrors. One primary advantage of this system architecture is that it does not require any laser beam or FOV folding mirrors, employs the few optical surfaces, and maximizes the return of laser light, and is easy to align. However, it is expected that this system design will most likely require a system housing having a height dimension which is greater than the height dimension required by the system design shown in Fig. 1B1.

As shown in Fig. 1Q2, PLIIM system of Fig. 1Q1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18; linear-type image formation and detection module 3 having an imaging subsystem with a fixed focal length imaging lens, a fixed focal distance, and a fixed field of view, and 1-D image detection array (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner. Preferably, the PLIIM system of Figs 1P1 and 102 is realized using the same or similar construction techniques shown in Figs. 1G1 through 1I2, and described above.

Third Alternative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 1A

In Fig. 1R1, the third illustrative embodiment of the PLIIM system of Figs. 1A, 1C are shown comprising: a 1-D type image formation and detection (IFD) module 3 having a field of view (FOV), as shown in Fig. 1B1; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams; and a pair of planar laser beam folding mirrors 37A and 37B arranged. The function of the planar laser illumination beam folding mirrors 37A and 37B is to fold the optical paths of the first and second planar laser illumination beams produced by the pair of planar illumination arrays 37A and 37B such that the field of view (FOV) of the image formation and detection module 3 is aligned in a direction that is coplanar with the planes of first and second planar laser illumination beams during object illumination and imaging operations. One notable disadvantage of this system architecture is that it requires additional optical surfaces which can reduce the intensity of outgoing laser illumination and therefore reduce slightly the intensity of returned laser illumination reflected off target objects. Also this system design requires a more complicated beam/FOV adjustment scheme, than not using any planar laser illumination beam folding mirrors. This system design can be best used when the planar laser illumination beams do not have large apex angles to provide sufficiently uniform illumination. In this system embodiment, the PLIMs are mounted on the optical bench as far back as possible from the beam folding mirrors, and cylindrical lenses with larger radiuses will be employed in the design of each PLIM.

As shown in Fig. 1R2, PLIIM system 1C shown in Fig. 1R1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 6A through 6B, and each planar laser illumination module being driven by a VLD driver circuit 18; linear-type image formation and detection module having an imaging subsystem with a fixed focal length imaging lens, a fixed focal distance, and a fixed field of view, and 1-D image detection array (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem; pair of planar laser beam folding mirrors 37A and 37B arranged so as to fold the optical paths of the first and second planar laser illumination beams produced by the pair of planar illumination arrays 6A and 6B; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Preferably, the PLIIM system of Figs 1Q1 and 1Q2 is realized using the same or similar construction techniques shown in Figs. 1G1 through 1I2, and described above.

Fourth Illustrative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 1A

In Fig. 1S1, the fourth illustrative embodiment of the PLIIM system of Figs. 1A, indicated by reference No. 1D is shown comprising: a 1-D type image formation and detection (IFD) module 3 having a field of view (FOV), as shown in Fig. 1B1; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams; a field of view folding mirror 9 for folding the field of view (FOV) of the image formation and detection module 3 about 90 degrees downwardly; and a pair of planar laser beam folding mirrors 37A and 37B arranged so as to fold the optical paths of the first and second planar laser illumination beams produced by the pair of planar illumination arrays 6A and 6B such that the planes of first and second planar laser illumination beams 7A and 7B are in a direction that is coplanar with the field of view of the image formation and detection module 3. Despite inheriting most of the disadvantages associated with the system designs shown in Figs. 1B1 and 1R1, this system architecture allows the length of the system housing to be easily minimized, at the expense of an increase in the height and width dimensions of the system housing.

As shown in Fig. 1S2, PLIIM system 1D shown in Fig. 1S1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18; linear-type image formation and detection module 3 having an imaging subsystem with a fixed focal length imaging lens, a fixed focal distance, and a fixed field of view, and 1-D image detection array (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem; a field of view folding mirror 9 for folding the field of view (FOV) of the image formation and detection module 3; a pair of planar laser beam folding mirrors 9 and 3 arranged so as to fold the optical paths of the first and second planar laser illumination beams produced by the pair of planar illumination arrays 37A and 37B; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner. Preferably, the PLIIM system of Figs 1S1 and 1S2 is realized using the same or similar construction techniques shown in Figs. 1G1 through 1I2, and described above.

Applications For The First Generalized Embodiment Of The PLIIM System Of The Present Invention, and the Illustrative Embodiments Thereof

Fixed focal distance PLIIM systems shown in Figs. 1B1 through 1U are ideal for applications in which there is little variation in the object distance, such as in a conveyor-type bottom scanner application. As such scanning systems employ a fixed focal length imaging lens, the image resolution requirements of such applications must be examined carefully to determine that the image resolution obtained is suitable for the intended application. Because the object distance is approximately constant for a bottom scanner application (i.e. the bar code almost always is illuminated and imaged within the same object plane), the dpi resolution of acquired images will be approximately constant. As image resolution is not a concern in this type of scanning applications, variable focal length (zoom) control is unnecessary, and a fixed focal length imaging lens should suffice and enable good results.

A fixed focal distance PLIIM system generally takes up less space than a variable or dynamic focus model because more advanced focusing methods require more complicated optics and electronics, and additional components such as motors. For this reason, fixed focus PLIIM systems are good choices for handheld and presentation scanners as indicated in Fig. 1U, wherein space and weight are always critical characteristics. In these applications, however, the object distance can vary over a range from several to a twelve or more inches, and so the designer must exercise care to ensure that the scanner's depth of field (DOF) alone will be sufficient to accommodate all possible variations in target object distance and orientation. Also, because a fixed focus imaging subsystem implies a fixed focal length camera lens, the variation in object distance implies that the dots per inch resolution of the image will vary as well. The focal length of the imaging lens must be chosen so that the angular width of the field of view (FOV) is narrow enough that the dpi image resolution will not fall below the minimum acceptable value anywhere within the range of object distances supported by the PLIIM system.

Second Generalized Embodiment Of The Planar Laser Illumination And Electronic Imaging System Of The Present Invention

The second generalized embodiment of the PLIIM system of the present invention 11 is illustrated in Figs. 1V1 and 1V2. As shown in Fig. 1V1, the PLIIM system 1' comprises: a housing 2 of compact construction; a linear (i.e. 1-dimensional) type image formation and detection (IFD) module 3'; and a pair of planar laser illumination arrays (PLIAs) 6A and 6B mounted on opposite sides of the IFD module 3'. During system operation, laser illumination arrays 6A and 6B each produce a moving plane of laser illumination beam 12' which synchronously moves and is disposed substantially coplanar with the field of view (FOV) of the

image formation and detection module 3', so as to scan a bar code symbol or other graphical structure 4 disposed stationary within a 3-D scanning region.

As shown in Figs. 2V2 and 2V3, the PLIIM system of Fig. 2V1 comprises: an image formation and detection module 3' having an imaging subsystem 3B' with a fixed focal length imaging lens, a fixed focal distance, and a fixed field of view, and a 1-D image detection array 3 (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem; a field of view sweeping mirror 9 operably connected to a motor mechanism 38 under control of camera control computer 22, for folding and sweeping the field of view of the image formation and detection module 3; a pair of planar laser illumination arrays 6A and 6B for producing planar laser illumination beams 7A and 7B; a pair of planar laser illumination beam folding/sweeping mirrors 37A and 37B operably connected to motor mechanisms 39A and 39B, respectively, under control of camera control computer 22, for folding and sweeping the planar laser illumination beams 7A and 7B, respectively, in synchronism with the FOV being swept by the FOV folding and sweeping mirror 9; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

An image formation and detection (IFD) module 3 having an imaging lens with a fixed focal length has a constant angular field of view (FOV); that is, the farther the target object is located from the IFD module, the larger the projection dimensions of the imaging subsystem's FOV become on the surface of the target object. A disadvantage to this type of imaging lens is that the resolution of the image that is acquired, in terms of pixels or dots per inch, varies as a function of the distance from the target object to the imaging lens. However, a fixed focal length imaging lens is easier and less expensive to design and produce than the alternative, a zoom-type imaging lens which will be discussed in detail hereinbelow with reference to Figs. 3A through 3J4.

Each planar laser illumination module 6A through 6B in PLIIM system 1' is driven by a VLD driver circuit 18 under the camera control computer 22. Notably, laser illumination beam folding/sweeping mirror 37A' and 38B', and FOV folding/sweeping mirror 9' are each rotatably driven by a motor-driven mechanism 38, 39A, and 39B, respectively, operated under the control of the camera control computer 22. These three mirror elements can be synchronously moved in a number of different ways. For example, the mirrors 37A', 37B' and 9' can be jointly rotated together under the control of one or more motor-driven mechanisms, or each mirror element can be driven by a separate driven motor which is synchronously controlled to enable the planar laser

illumination beams 7A, 7B and FOV 10 to move together in a spatially-coplanar manner during illumination and detection operations within the PLIIM system.

In accordance with the present invention, the planar laser illumination arrays 6A and 6B, the linear image formation and detection module 3, the folding/sweeping FOV mirror 9', and the planar laser illumination beam folding/sweeping mirrors 37A' and 37B' employed in this generalized system embodiment, are fixedly mounted on an optical bench or chassis 8 so as to prevent any relative motion (which might be caused by vibration or temperature changes) between: (i) the image forming optics (e.g. imaging lens) within the image formation and detection module 3 and the FOV folding/sweeping mirror 9' employed therewith; and (ii) each planar laser illumination module (i.e. VLD/cylindrical lens assembly) and the planar laser illumination beam folding/sweeping mirrors 37A' and 37B' employed in this PLIIM system configuration. Preferably, the chassis assembly should provide for easy and secure alignment of all optical components employed in the planar laser illumination arrays 6A' and 6B' , beam folding/sweeping mirrors 37A' and 37B', the image formation and detection module 3 and FOV folding/sweeping mirror 9', as well as be easy to manufacture, service and repair. Also, this generalized PLIIM system embodiment 1' employs the general "planar laser illumination" and "focus beam at farthest object distance (FBAFOD)" principles described above.

<u>Applications For The Second Generalized Embodiment Of The PLIIM System Of The Present Invention</u>

The fixed focal length PLIIM system shown in Figs. 1V1-1V3 has a 3-D fixed field of view which, while spatially-aligned with a composite planar laser illumination beam 12 in a coplanar manner, is automatically swept over a 3-D scanning region within which bar code symbols and other graphical indicia 4 may be illuminated and imaged in accordance with the principles of the present invention. As such, this generalized embodiment of the present invention is ideally suited for use in hand-supportable and hands-free presentation type bar code symbol readers shown in Figs. 1V4 and 1V5, respectively, in which rasterlike-scanning (i.e. up and down) patterns can be used for reading 1-D as well as 2-D bar code symbologies such as the PDF 147 symbology. In general, the PLIM system of this generalized embodiment may have any of the housing form factors disclosed and described in Applicant's copending US Application Nos. 09/204,176 entitled filed December 3, 1998 and 09/452,976 filed December 2, 1999, and WIPO Publication No. WO 00/33239 published June 8, 2000, incorporated herein by reference. The beam sweeping technology disclosed in copending Application No. 08/931,691 filed September 16, 1997, incorporated herein by reference, can be used to uniformly sweep both the planar laser illumination beam and linear FOV in a coplanar manner during illumination and imaging operations.

<u>Third Generalized Embodiment Of The PLIIM System Of The Present Invention</u>

The third generalized embodiment of the PLIIM system of the present invention 40 is illustrated in Fig. 2A. As shown therein, the PLIIM system 40 comprises: a housing 2 of compact construction; a linear (i.e. 1-dimensional) type image formation and detection (IFD) module 3' including a 1-D electronic image detection array 3A, a linear (1-D) imaging subsystem (LIS) 3B' having a fixed focal length, a variable focal distance, and a fixed field of view (FOV), for forming a 1-D image of an illuminated object located within the fixed focal distance and FOV thereof and projected onto the 1-D image detection array 3A, so that the 1-D image detection array 3A can electronically detect the image formed thereon and automatically produce a digital image data set 5 representative of the detected image for subsequent image processing; and a pair of planar laser illumination arrays (PLIAs) 6A and 6B , each mounted on opposite sides of the IFD module 3', such that each planar laser illumination array 6A and 6B produces a composite plane of laser beam illumination 12 which is disposed substantially coplanar with the field view of the image formation and detection module 3' during object illumination and image detection operations carried out by the PLIIM system.

In accordance with the present invention, the planar laser illumination arrays 6A and 6B, the linear image formation and detection module 3', and any non-moving FOV and/or planar laser illumination beam folding mirrors employed in any configuration of this generalized system embodiment, are fixedly mounted on an optical bench or chassis so as to prevent any relative motion (which might be caused by vibration or temperature changes) between: (i) the image forming optics (e.g. imaging lens) within the image formation and detection module 3' and any stationary FOV folding mirrors employed therewith; and (ii) each planar laser illumination module (i.e. VLD/cylindrical lens assembly) and any planar laser illumination beam folding mirrors employed in the PLIIM system configuration. Preferably, the chassis assembly should provide for easy and secure alignment of all optical components employed in the planar laser illumination arrays 6A and 6B as well as the image formation and detection module 3', as well as be easy to manufacture, service and repair. Also, this generalized PLIIM system embodiment 40 employs the general "planar laser illumination" and "focus beam at farthest object distance (FBAFOD)" principles described above. Various illustrative embodiments of this generalized PLIIM system will be described below.

An image formation and detection (IFD) module 3 having an imaging lens with variable focal distance, as employed in the PLIIM system of Fig. 2A, can adjust its image distance to compensate for a change in the target's object distance; thus, at least some of the component lens elements in the imaging subsystem are movable, and the depth of field of the imaging subsystems does not limit the ability of the imaging subsystem to accommodate possible object distances and orientations. A variable focus imaging subsystem is able to move its components in such a way as to change the image distance of the imaging lens to compensate for a change in the target's object distance, thus preserving good focus no matter where the target object might be located. Variable focus can be accomplished in several ways, namely: by moving lens elements; moving imager detector/sensor; and dynamic focus. Each of these different methods will be summarized below for sake of convenience.

Use Of Moving Lens Elements In The Image Formation And Detection Module

The imaging subsystem in this generalized PLIIM system embodiment can employ an imaging lens which is made up of several component lenses contained in a common lens barrel. A variable focus type imaging lens such as this can move one or more of its lens elements in order to change the effective distance between the lens and the image sensor, which remains stationary. This change in the image distance compensates for a change in the object distance of the target object and keeps the return light in focus. The position at which the focusing lens element(s) must be in order to image light returning from a target object at a given object distance is determined by consulting a lookup table, which must be constructed ahead of time, either experimentally or by design software, well known in the optics art.

Use Of An Moving Image Detection Array In The Image Formation And Detection Module

The imaging subsystem in this generalized PLIIM system embodiment can be constructed so that all the lens elements remain stationary, with the imaging detector/sensor array being movable relative to the imaging lens so as to change the image distance of the imaging subsystem. The position at which the image detector/sensor must be located to image light returning from a target at a given object distance is determined by consulting a lookup table, which must be constructed ahead of time, either experimentally or by design software, well known in the art.

Use Of Dynamic Focal Distance Control In The Image Formation And Detection Module

The imaging subsystem in this generalized PLIIM system embodiment can be designed to embody a "dynamic" form of variable focal distance (i.e. focus) control, which is an advanced form of variable focus control. In conventional variable focus control schemes, one focus (i.e. focal distance) setting is established in anticipation of a given target object. The object is imaged using that setting, then another setting is selected for the next object image, if necessary. However, depending on the shape and orientation of the target object, a single target object may exhibit enough variation in its distance from the imaging lens to make it impossible for a single focus setting to acquire a sharp image of the entire object. In this case, the imaging subsystem must change its focus setting while the object is being imaged. This adjustment does not have to be made continuously; rather, a few discrete focus settings will generally be sufficient. The exact number will depend on the shape and orientation of the package being imaged and the depth of field of the imaging subsystem used in the IFD module.

It should be noted that dynamic focus control is only used with a linear image detection/sensor array, as used in the system embodiments shown in Figs. 2A through 3J4. The reason for this limitation is quite clear: an area-type image detection array captures an entire

image after a rapid number of exposures to the planar laser illumination beam, and although changing the focus setting of the imaging subsystem might clear up the image in one part of the detector array, it would induce blurring in another region of the image, thus failing to improve the overall quality of the acquired image.

First Illustrative Embodiment Of The PLIIM System Shown In Fig. 2A

The first illustrative embodiment of the PLIIM system of Fig. 2A 40A is shown in Fig. 2B1. As illustrated therein, the field of view of the image formation and detection module 3' and the first and second planar laser illumination beams 7A and 7B produced by the planar illumination arrays 6A and 6B, respectively, are arranged in a substantially coplanar relationship during object illumination and image detection operations.

The PLIIM system illustrated in Fig. 2B1 is shown in greater detail in Fig. 2B2. As shown therein, the linear image formation and detection module 3' is shown comprising an imaging subsystem 3B', and a linear array of photo-electronic detectors 3A realized using CCD technology (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) for detecting 1-D line images (e.g. 6000 pixels, @ 60MHZ scanning rate) formed thereon by the imaging subsystem 3B', providing an image resolution of 200dpi or 8 pixels/mm, as the image resolution that results from a fixed focal length imaging lens is the function of the object distance (i.e. the longer the object distance, the lower the resolution). The imaging subsystem 3B' has a fixed focal length imaging lens (e.g. 80mm Pentax lens, F4.5), a fixed field of view (FOV), and a variable focal distance imaging capability (e.g. 36" total scanning range), and an auto-focusing image plane with a response time of about 20-30 milliseconds over about 5mm working range.

As shown, each planar laser illumination array (PLIA) 6A, 6B comprises a plurality of planar laser illumination modules (PLIMs) 11A through 11F, closely arranged relative to each other, in a rectilinear fashion. As taught hereinabove, the relative spacing and orientation of each PLIM 11 is such that the spatial intensity distribution of the individual planar laser beams 7A, 7B superimpose and additively produce composite planar laser illumination beam 12 having a substantially uniform power density distribution along the widthwise dimensions of the laser illumination beam, throughout the entire working range of the PLIIM system.

As shown in Fig. 2C1, the PLIIM system of Fig. 2B1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18; linear-type image formation and detection module 3A; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3A, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms

(including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 2C2 illustrates in greater detail the structure of the IFD module 3' used in the PLIIM system of Fig. 2B1. As shown, the IFD module 3' comprises a variable focus fixed focal length imaging subsystem 3B' and a 1-D image detecting array 3A mounted along an optical bench 30 contained within a common lens barrel (not shown). The imaging subsystem 3B' comprises a group of stationary lens elements 3B' mounted along the optical bench before the image detecting array 3A, and a group of focusing lens elements 3B' (having a fixed effective focal length) mounted along the optical bench in front of the stationary lens elements 3A1. In a non-customized application, focal distance control can be provided by moving the 1-D image detecting array 3A back and forth along the optical axis with an optical element translator 3C in response to a first set of control signals 3E generated by the camera control computer 22, while the entire group of focal lens elements remain stationary. Alternatively, focal distance control can also be provided by moving the entire group of focal lens elements back and forth with translator 3C in response to a first set of control signals 3E generated by the camera control computer, while the 1-D image detecting array 3A remains stationary. In customized applications, it is possible for the individual lens elements in the group of focusing lens elements 3B' to be moved in response to control signals generated by the camera control computer 22. Regardless of the approach taken, an IFD module 3' with variable focus fixed focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

Second Illustrative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 2A

The second illustrative embodiment of the PLIIM system of Fig. 2A 40B is shown in Fig. 2D1 comprising: an image formation and detection module 3' having an imaging subsystem 3B' with a fixed focal length imaging lens, a variable focal distance and a fixed field of view, and a linear array of photo-electronic detectors 3A realized using CCD technology (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem 3B'; a field of view folding mirror 9 for folding the field of view of the image formation and detection module 3'; and a pair of planar laser illumination arrays 6A and 6B arranged in relation to the image formation and detection module 3' such that the field of view thereof folded by the field of view folding mirror 9 is oriented in a direction that is coplanar with the composite plane of laser illumination 12 produced by the planar illumination arrays, during object illumination and image detection operations, without using any laser beam folding mirrors.

One primary advantage of this system design is that it enables a construction having an ultra-low height profile suitable, for example, in unitary package identification and dimensioning systems of the type disclosed in Figs. 17-22, wherein the image-based bar code symbol reader needs to be installed within a compartment (or cavity) of a housing having relatively low height dimensions. Also, in this system design, there is a relatively high degree of freedom provided in where the image formation and detection module 3' can be mounted on the optical bench of the system, thus enabling the field of view (FOV) folding technique disclosed in Fig. 1L1 to be practiced in a relatively easy manner.

As shown in Fig. 2D2, the PLIIM system of Fig. 2D1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18; linear-type image formation and detection module 3'; a field of view folding mirror 9 for folding the field of view of the image formation and detection module 3'; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3', for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 2D2 illustrates in greater detail the structure of the IFD module 3' used in the PLIIM system of Fig. 2D1. As shown, the IFD module 3' comprises a variable focus fixed focal length imaging subsystem 3B' and a 1-D image detecting array 3A mounted along an optical bench 3D contained within a common lens barrel (not shown). The imaging subsystem 3B' comprises a group of stationary lens elements 3A' mounted along the optical bench before the image detecting array 3A', and a group of focusing lens elements 3B' (having a fixed effective focal length) mounted along the optical bench in front of the stationary lens elements 3A1. In a non-customized application, focal distance control can be provided by moving the 1-D image detecting array 3A back and forth along the optical axis with a translator 3E, in response to a first set of control signals 3E generated by the camera control computer 22, while the entire group of focal lens elements remain stationary. Alternatively, focal distance control can also be provided by moving the entire group of focal lens elements 3B' back and forth with translator 3C in response to a first set of control signals 3E generated by the camera control computer 22, while the 1-D image detecting array 3A remains stationary. In customized applications, it is possible for the individual lens elements in the group of focusing lens elements 3B' to be moved in response to control signals generated by the camera control computer. Regardless of the approach taken, an IFD module 3' with variable focus fixed focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

Third Illustrative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 2A

The second illustrative embodiment of the PLIIM system of Fig. 2A 40C is shown in Fig. 2D1 comprising: an image formation and detection module 3' having an imaging subsystem 3B' with a fixed focal length imaging lens, a variable focal distance and a fixed field of view, and a linear array of photo-electronic detectors 3A realized using CCD technology (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem 3B'; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams 7A, 7B, and a pair of planar laser beam folding mirrors 37A and 37B for folding the planes of the planar laser illumination beams produced by the pair of planar illumination arrays 6A and 6B, in a direction that is coplanar with the plane of the field of view of the image formation and detection during object illumination and image detection operations.

The primary disadvantage of this system architecture is that it requires additional optical surfaces (i.e. the planar laser beam folding mirrors) which reduce outgoing laser light and therefore the return laser light slightly. Also this embodiment requires a complicated beam/FOV adjustment scheme. Thus, this system design can be best used when the planar laser illumination beams do not have large apex angles to provide sufficiently uniform illumination. Notably, in this system embodiment, the PLIMs are mounted on the optical bench 8 as far back as possible from the beam folding mirrors 37A, 37B, and cylindrical lenses 16 with larger radiuses will be employed in the design of each PLIM 11.

As shown in Fig. 2E2, the PLIIM system of Fig. 2E1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18; linear-type image formation and detection module 3'; a field of view folding mirror 9 for folding the field of view of the image formation and detection module 3'; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3A, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 2E3 illustrates in greater detail the structure of the IFD module 3' used in the PLIIM system of Fig. 2E1. As shown, the IFD module 3' comprises a variable focus fixed focal length

imaging subsystem 3B' and a 1-D image detecting array 3Amounted along an optical bench 3D contained within a common lens barrel (not shown). The imaging subsystem 3B' comprises a group of stationary lens elements 3A1 mounted along the optical bench before the image detecting array 3A, and a group of focusing lens elements 3B' (having a fixed effective focal length) mounted along the optical bench in front of the stationary lens elements 3A1. In a non-customized application, focal distance control can be provided by moving the 1-D image detecting array 3A back and forth along the optical axis in response to a first set of control signals 3E generated by the camera control computer 22, while the entire group of focal lens elements 3B' remain stationary. Alternatively, focal distance control can also be provided by moving the entire group of focal lens elements 3B' back and forth with translator 3C in response to a first set of control signals 3E generated by the camera control computer 22, while the 1-D image detecting array 3A remains stationary. In customized applications, it is possible for the individual lens elements in the group of focusing lens elements 3B' to be moved in response to control signals generated by the camera control computer 22. Regardless of the approach taken, an IFD module 3' with variable focus fixed focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

<u>Fourth Illustrative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 2A</u>

The fourth illustrative embodiment of the PLIIM system of Fig. 2A 40D is shown in Fig. 2F1 comprising: an image formation and detection module 3' having an imaging subsystem 3B' with a fixed focal length imaging lens, a variable focal distance and a fixed field of view, and a linear array of photo-electronic detectors 3A realized using CCD technology (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem 3B'; a field of view folding mirror 9 for folding the FOV of the imaging subsystem 3B'; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams; and a pair of planar laser beam folding mirrors 37A and 37B arranged in relation to the planar laser illumination arrays 6A and 6B so as to fold the optical paths of the first and second planar laser illumination beams 7A, 7B in a direction that is coplanar with the folded FOV of the image formation and detection module 3', during object illumination and image detection operations.

As shown in Fig. 2F2, the PLIIM system 40D of Fig. 2F1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11B, and each planar laser illumination module being driven by a VLD driver circuit 18; linear-type image formation and detection module 3'; a field of view folding mirror 9 for folding the field of view of the image formation and detection module 3'; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3A, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the

object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 2F3 illustrates in greater detail the structure of the IFD module 3' used in the PLIIM system of Fig. 2F1. As shown, the IFD module 3' comprises a variable focus fixed focal length imaging subsystem 3B' and a 1-D image detecting array 3A mounted along an optical bench 3D contained within a common lens barrel (not shown). The imaging subsystem 3B' comprises a group of stationary lens elements 3A1 mounted along the optical bench 3D before the image detecting array 3A, and a group of focusing lens elements 3B' (having a fixed effective focal length) mounted along the optical bench in front of the stationary lens elements 3A1. In a non-customized application, focal distance control can be provided by moving the 1-D image detecting array 3A back and forth along the optical axis with translator 3C in response to a first set of control signals 3E generated by the camera control computer 22, while the entire group of focal lens elements 3B' remain stationary. Alternatively, focal distance control can also be provided by moving the entire group of focal lens elements 3B' back and forth with translator 3C in response to a first set of control signals 3E generated by the camera control computer 22, while the 1-D image detecting array 3A remains stationary. In customized applications, it is possible for the individual lens elements in the group of focusing lens elements 3B' to be moved in response to control signals generated by the camera control computer 22. Regardless of the approach taken, an IFD module with variable focus fixed focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

<u>Applications For The Third Generalized Embodiment Of The PLIIM System Of The Present Invention, and the Illustrative Embodiments Thereof</u>

As the PLIIM systems shown in Figs. 2A through 2F3 employ an IFD module 3' having a linear image detecting array and an imaging subsystem having variable focus (i.e. focal distance) control, such PLIIM systems are good candidates for use in a conveyor top scanner application, as shown in Figs. 2G, as the variation in target object distance can be up to a meter or more (from the imaging subsystem). In general, such object distances are too great a range for the depth of field (DOF) characteristics of the imaging subsystem alone to accommodate such object distance parameter variations during object illumination and imaging operations. Provision for variable focal distance control is generally sufficient for the conveyor top scanner application shown in Fig. 2G, as the demands on the depth of field and variable focus or dynamic focus control characteristics of such PLIIM system are not as severe in the conveyor top scanner application, as they might be in the conveyor side scanner application, also illustrated in Fig. 2G.

Notably, by adding dynamic focusing functionality to the imaging subsystem of any of the embodiments shown in Figs. 2A through 2F3, the resulting PLIIM system becomes appropriate for the conveyor side-scanning application discussed above, where the demands on the depth of field and variable focus or dynamic focus requirements are greater compared to a conveyor top scanner application.

Fourth Generalized Embodiment Of The PLIIM System Of The Present Invention

The fourth generalized embodiment of the PLIIM system 40' of the present invention is illustrated in Figs. 2I1 and 2I2. As shown in Fig. 2I1, the PLIIM system 40' comprises: a housing 2 of compact construction; a linear (i.e. 1-dimensional) type image formation and detection (IFD) module 3'; and a pair of planar laser illumination arrays (PLIAs) 6A and 6B mounted on opposite sides of the IFD module 3'. During system operation, laser illumination arrays 6A and 6B each produce a moving planar laser illumination beam 12' which synchronously moves and is disposed substantially coplanar with the field of view (FOV) of the image formation and detection module 3', so as to scan a bar code symbol or other graphical structure 4 disposed stationary within a 3-D scanning region.

As shown in Figs. 2I2 and 2I3, the PLIIM system of Fig. 2I1 comprises: an image formation and detection module 3' having an imaging subsystem 3B' with a fixed focal length imaging lens, a variable focal distance and a fixed field of view, and a linear array of photo-electronic detectors 3A realized using CCD technology (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem 3B'; a field of view folding and sweeping mirror 9' for folding and sweeping the field of view 10 of the image formation and detection module 3'; a pair of planar laser illumination arrays 6A and 6B for producing planar laser illumination beams 7A and 7B; a pair of planar laser illumination beam sweeping mirrors 37A' and 37B' for folding and sweeping the planar laser illumination beams 7A and 7B, respectively, in synchronism with the FOV being swept by the FOV folding and sweeping mirror 9'; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3A, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner. As shown in Fig. 2F2, each planar laser illumination module 11A through 11F, is driven by a VLD driver circuit 18 under the camera control computer 22. Notably, laser illumination beam folding/sweeping mirrors 37A'

and 37B', and FOV folding/sweeping mirror 9' are each rotatably driven by a motor-driven mechanism 39A, 39B, 38, respectively, operated under the control of the camera control computer 22. These three mirror elements can be synchronously moved in a number of different ways. For example, the mirrors 37A', 37B' and 9' can be jointly rotated together under the control of one or more motor-driven mechanisms, or each mirror element can be driven by a separate driven motor which are synchronously controlled to enable the composite planar laser illumination beam and FOV to move together in a spatially-coplanar manner during illumination and detection operations within the PLIIM system.

Fig. 2I4 illustrates in greater detail the structure of the IFD module 3' used in the PLIIM system of Fig. 2I1. As shown, the IFD module 3' comprises a variable focus fixed focal length imaging subsystem 3B' and a 1-D image detecting array 3A mounted along an optical bench 3D contained within a common lens barrel (not shown). The imaging subsystem 3B' comprises a group of stationary lens elements 3A1 mounted along the optical bench before the image detecting array 3A, and a group of focusing lens elements 3B' (having a fixed effective focal length) mounted along the optical bench in front of the stationary lens elements 3A1. In a non-customized application, focal distance control can be provided by moving the 1-D image detecting array 3A back and forth along the optical axis in response to a first set of control signals 3E generated by the camera control computer 22, while the entire group of focal lens elements 3B' remain stationary. Alternatively, focal distance control can also be provided by moving the entire group of focal lens elements 3B' back and forth with a translator 3C in response to a first set of control signals 3E generated by the camera control computer 22, while the 1-D image detecting array 3A remains stationary. In customized applications, it is possible for the individual lens elements in the group of focusing lens elements 3B' to be moved in response to control signals generated by the camera control computer 22. Regardless of the approach taken, an IFD module 3' with variable focus fixed focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

In accordance with the present invention, the planar laser illumination arrays 6A and 6B, the linear image formation and detection module 3', the folding/sweeping FOV mirror 9', and the planar laser illumination beam folding/sweeping mirrors 37A' and 37B' employed in this generalized system embodiment, are fixedly mounted on an optical bench or chassis 8 so as to prevent any relative motion (which might be caused by vibration or temperature changes) between: (i) the image forming optics (e.g. imaging lens) within the image formation and detection module 3' and the FOV folding/sweeping mirror 9' employed therewith; and (ii) each planar laser illumination module (i.e. VLD/cylindrical lens assembly) and the planar laser illumination beam folding/sweeping mirrors 37A' and 37B' employed in this PLIIM system configuration. Preferably, the chassis assembly should provide for easy and secure alignment of all optical components employed in the planar laser illumination arrays 6A and 6B , beam folding/sweeping mirrors 37A' and 37B', the image formation and detection module 3' and FOV folding/sweeping mirror 9', as well as be easy to manufacture, service and repair. Also, this

generalized PLIIM system embodiment 40' employs the general "planar laser illumination" and "focus beam at farthest object distance (FBAFOD)" principles described above.

Applications For The Fourth Generalized Embodiment Of The PLIIM System Of The Present Invention

As the PLIIM systems shown in Figs. 2I1 through 2I4 employ (i) an IFD module having a linear image detecting array and an imaging subsystem having variable focus (i.e. focal distance) control, and (ii) a mechanism for automatically sweeping both the planar (2-D) FOV and planar laser illumination beam through a 3-D scanning field in an "up and down" pattern while maintaining the inventive principle of "laser-beam/FOV coplanarity" hereindisclosed, such PLIIM systems are good candidates for use in a hand-held scanner application, shown in Figs. 2I5, and the hands-free presentation scanner application illustrated in Fig. 2I6. The provision of variable focal distance control in these illustrative PLIIM systems is most sufficient for the hand-held scanner application shown in Fig. 2I5, and presentation scanner application shown in Figs. 2I6, as the demands placed on the depth of field and variable focus control characteristics of such systems will not be severe.

Fifth Generalized Embodiment Of The PLIIM System Of The Present Invention

The fifth generalized embodiment of the PLIIM system of the present invention 50 is illustrated in Fig. 3A. As shown therein, the PLIIM system 50 comprises: a housing 2 of compact construction; a linear (i.e. 1-dimensional) type image formation and detection (IFD) module 3" including a 1-D electronic image detection array 3A, a linear (1-D) imaging subsystem (LIS) 3B" having a variable focal length, a variable focal distance, and a variable field of view (FOV), for forming a 1-D image of an illuminated object located within the fixed focal distance and FOV thereof and projected onto the 1-D image detection array 3A, so that the 1-D image detection array 3A can electronically detect the image formed thereon and automatically produce a digital image data set 5 representative of the detected image for subsequent image processing; and a pair of planar laser illumination arrays (PLIAs) 6A and 6B, each mounted on opposite sides of the IFD module 3", such that each planar laser illumination array 6A and 6B produces a plane of laser beam illumination 7A, 7B which is disposed substantially coplanar with the field view of the image formation and detection module 3" during object illumination and image detection operations carried out by the PLIIM system.

In the PLIIM system of Fig. 3A, the linear image formation and detection (IFD) module 3" has an imaging lens with a variable focal length (i.e. a zoom-type imaging lens) 3B1, that has a variable angular field of view (FOV); that is, the farther the target object is located from the IFD module, the larger the projection dimensions of the imaging subsystem's FOV become on the surface of the target object. A zoom imaging lens is capable of changing its focal length, and therefore its angular field of view (FOV) by moving one or more of its component lens elements.

The position at which the zooming lens element(s) must be in order to achieve a given focal length is determined by consulting a lookup table, which must be constructed ahead of time either experimentally or by design software, in a manner well known in the art. An advantage to using a zoom lens is that the resolution of the image that is acquired, in terms of pixels or dots per inch, remains constant no matter what the distance from the target object to the lens. However, a zoom camera lens is more difficult and more expensive to design and produce than the alternative, a fixed focal length camera lens.

The image formation and detection (IFD) module 3" in the PLIIM system of Fig. 3A also has an imaging lens 3B2 with variable focal distance, which can adjust its image distance to compensate for a change in the target's object distance. Thus, at least some of the component lens elements in the imaging subsystem 3B2 are movable, and the depth of field (DOF) of the imaging subsystem does not limit the ability of the imaging subsystem to accommodate possible object distances and orientations. This variable focus imaging subsystem 3B2 is able to move its components in such a way as to change the image distance of the imaging lens to compensate for a change in the target's object distance, thus preserving good image focus no matter where the target object might be located. This variable focus technique can be practiced in several different ways, namely: by moving lens elements in the imaging subsystem; by moving the image detection/sensing array relative to the imaging lens; and by dynamic focus control. Each of these different methods has been described in detail above.

In accordance with the present invention, the planar laser illumination arrays 6A and 6B the image formation and detection module 3" are fixedly mounted on an optical bench or chassis assembly 8 so as to prevent any relative motion between (i) the image forming optics (e.g. camera lens) within the image formation and detection module 3" and (ii) each planar laser illumination module (i.e. VLD/cylindrical lens assembly) employed in the PLIIM system which might be caused by vibration or temperature changes. Preferably, the chassis assembly should provide for easy and secure alignment of all optical components employed in the planar laser illumination arrays 6A and 6B as well as the image formation and detection module 3", as well as be easy to manufacture, service and repair. Also, this PLIIM system employs the general "planar laser illumination" and "FBAFOD" principles described above.

First Illustrative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 3B1

The first illustrative embodiment of the PLIIM system of Fig. 3A 50A is shown in Fig. 3B1. As illustrated therein, the field of view of the image formation and detection module 3" and the first and second planar laser illumination beams 7A and 7B produced by the planar illumination arrays 6A and 6B, respectively, are arranged in a substantially coplanar relationship during object illumination and image detection operations.

The PLIIM system 50A illustrated in Fig. 3B1 is shown in greater detail in Fig. 3B2. As shown therein, the linear image formation and detection module 3" is shown comprising an

imaging subsystem 3B", and a linear array of photo-electronic detectors 3A realized using CCD technology (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem 3B". The imaging subsystem 3B" has a variable focal length imaging lens, a variable focal distance and a variable field of view. As shown, each planar laser illumination array 6A, 6B comprises a plurality of planar laser illumination modules (PLIMs) 11A through 11F, closely arranged relative to each other, in a rectilinear fashion. As taught hereinabove, the relative spacing of each PLIM 11 is such that the spatial intensity distribution of the individual planar laser beams superimpose and additively provide a composite planar case illumination beam having substantially uniform composite spatial intensity distribution for the entire planar laser illumination array 6A and 6B.

As shown in Fig. 3C1, the PLIIM system 50A of Fig. 3B1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18; linear-type image formation and detection module 3"; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3A, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 3C2 illustrates in greater detail the structure of the IFD module 3" used in the PLIIM system of Fig. 3B1. As shown, the IFD module 3" comprises a variable focus variable focal length imaging subsystem 3B" and a 1-D image detecting array 3A mounted along an optical bench 3D contained within a common lens barrel (not shown). In general, the imaging subsystem 3B' comprises: a first group of focal lens elements 3A1 mounted stationary relative to the image detecting array 3A; a second group of lens elements 3B2, functioning as a focal lens assembly, movably mounted along the optical bench in front of the first group of stationary lens elements 3A1; and a third group of lens elements 3B1 , functioning as a zoom lens assembly, movably mounted between the second group of focal lens elements and the first group of stationary focal lens elements 3A1. In a non-customized application, focal distance control can also be provided by moving the second group of focal lens elements 3B2 back and forth with translator 3C1 in response to a first set of control signals generated by the camera control computer 22, while the 1-D image detecting array 3A remains stationary. Alternatively, focal distance control can be provided by moving the 1-D image detecting array 3A back and forth along the optical axis with translator 3C1 in response to a first set of control signals 3E2 generated by the camera control computer 22, while the second group of focal lens elements 3B2

remain stationary. For zoom control (i.e. variable focal length control), the focal lens elements in the third group 3B2 are typically moved relative to each other with translator 3C1 in response to a second set of control signals 3E2 generated by the camera control computer 22. Regardless of the approach taken in any particular illustrative embodiment, an IFD module with variable focus variable focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

A first preferred implementation of the image formation and detection (IFD) subsystem of Fig. 3C2 is shown in Fig. 3D1. As shown in Fig. 3D1, IFD subsystem 3" comprises: an optical bench 3D having a pair of rails, along which mounted optical elements are translated; a linear CCD-type image detection array 3A (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) fixedly mounted to one end of the optical bench; a system of stationary lenses 3A1 fixedly mounted before the CCD-type linear image detection array 3A; a first system of movable lenses 3B1 slidably mounted to the rails of the optical bench 3D by a set of ball bearings, and designed for stepped movement relative to the stationary lens subsystem 3A1 with translator 3C1 in automatic response to a first set of control signals 3E1 generated by the camera control computer 22; and a second system of movable lenses 3B2 slidably mounted to the rails of the optical bench by way of a second set of ball bearings, and designed for stepped movements relative to the first system of movable lenses 3B with translator 3C2 in automatic response to a second set of control signals 3D2 generated by the camera control computer 22. As shown in Fig. 3D, a large stepper wheel 42 driven by a zoom stepper motor 43 engages a portion of the zoom lens system 3B1 to move the same along the optical axis of the stationary lens system 3A1 in response to control signals 3C1 generated from the camera control computer 22. Similarly, a small stepper wheel 44 driven by a focus stepper motor 45 engages a portion of the focus lens system 3B2 to move the same along the optical axis of the stationary lens system 3A1in response to control signals 3E2 generated from the camera control computer 22.

A second preferred implementation of the IFD subsystem of Fig. 3C2 is shown in Figs. 3D2 and 3D3. As shown in Figs. 3D2 and 3D3, IFD subsystem 3" comprises: an optical bench (i.e. camera body) 400 having a pair of side rails 401A and 401B, along which mounted optical elements are translated; a linear CCD-type image detection array 3A (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) fixedly mounted to one end of the optical bench; a system of stationary lenses 3A1 fixedly mounted before the CCD-type linear image detection array 3A; a first movable (zoom) lens system 402 including a first electrical rotary motor 403 mounted to the camera body 400, an arm structure 404 mounted to the shaft of the motor 403, a first lens mounting fixture 405 (supporting a zoom lens group) 406 slidably mounted to camera body on first rail structure 401A, and a first linkage member 407 pivotally connected to a first slidable lens mount 408 and the free end of the first arm structure 404 so that as the first motor shaft rotates, the first slidable lens mount 405 moves along the optical axis of the imaging optics supported within the camera body; a second movable (focus) lens system 410 including a second

electrical rotary motor 411 mounted to the camera body 400, a second arm structure 412 mounted to the shaft of the second motor 411, a second lens mounting fixture 413 (supporting a focal lens group 414) slidably mounted to the camera body on a second rail structure 401B, and a second linkage member 415 pivotally connected to a second slidable lens mount 416 and the free end of the second arm structure 412 so that as the second motor shaft rotates, the second slidable lens mount 413 moves along the optical axis of the imaging optics supported within the camera body. Notably, the first system of movable lenses 406 are designed for relative small stepped movement relative to the stationary lens subsystem 3A1 with in automatic response to a first set of control signals 3E1 generated by the camera control computer 22 and transmitted to the first electrical motor 403. The second system of movable lenses 414 are designed for relatively larger stepped movements relative to the first system of movable lenses 406 in automatic response to a second set of control signals 3D2 generated by the camera control computer 22 and transmitted to the second electrical motor 411.

<u>Method of Adjusting the Focal Characteristics of the Planar Laser Illumination Beams Generated by Planar Laser Illumination Arrays Used in Conjunction with Image Formation And Detection Modules Employing Variable Focal Length (Zoom) Imaging Lenses</u>

Unlike the fixed focal length imaging lens case, there occurs a significant a $1/r^2$ drop-off in laser return light intensity at the image detection array when using a zoom (variable focal length) imaging lens in the PLIIM system hereof. In PLIIM system employing an imaging subsystem having a variable focal length imaging lens, the area of the imaging subsystem's field of view (FOV) remains constant as the working distance increases. Such variable focal length control is used to ensure that each image formed and detected by the image formation and detection (IFD) module 3" has the same number of "dots per inch" (DPI) resolution, regardless of the distance of the target object from the IFD module 3". However, since module's field of view does not increase in size with the object distance, equation (8) must be rewritten as the equation (10) set forth below

$$E_{ccd}^{zoom} = \frac{E_0 f^2 s^2}{8d^2 F^2 r^2} \tag{10}$$

where s^2 is the area of the field of view and d^2 is the area of a pixel on the image detecting array. This expression is a strong function of the object distance, and demonstrates $1/r^2$ drop off of the return light. If a zoom lens is to be used, then it is desirable to have a greater power density at the farthest object distance than at the nearest, to compensate for this loss. Again, focusing the beam at the farthest object distance is the technique that will produce this result.

Therefore, in summary, where a variable focal length (i.e. zoom) imaging subsystem is employed in the PLIIM system, the planar laser beam focusing technique of the present invention described above helps compensate for (i) decreases in the power density of the incident

illumination beam due to the fact that the width of the planar laser illumination beam increases for increasing distances away from the imaging subsystem, and (ii) any $1/r^2$ type losses that would typically occur when using the planar laser planar illumination beam of the present invention.

<u>Second Illustrative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 3A</u>

The second illustrative embodiment of the PLIIM system of Fig. 3A 50B is shown in Fig. 3E1 comprising: an image formation and detection module 3" having an imaging subsystem 3B with a variable focal length imaging lens, a variable focal distance and a variable field of view, and a linear array of photo-electronic detectors 3A realized using CCD technology (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem 3B"; a field of view folding mirror 9 for folding the field of view of the image formation and detection module 3"; and a pair of planar laser illumination arrays 6A and 6B arranged in relation to the image formation and detection module 3" such that the field of view thereof folded by the field of view folding mirror 9 is oriented in a direction that is coplanar with the composite plane of laser illumination 12 produced by the planar illumination arrays, during object illumination and image detection operations, without using any laser beam folding mirrors.

As shown in Fig. 3E2, the PLIIM system of Fig. 3E1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18; linear-type image formation and detection module 3A; a field of view folding mirror 9' for folding the field of view of the image formation and detection module 3"; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3", for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 3E3 illustrates in greater detail the structure of the IFD module 3" used in the PLIIM system of Fig. 3E1. As shown, the IFD module 3" comprises a variable focus variable focal length imaging subsystem 3B" and a 1-D image detecting array 3A mounted along an optical bench 3D contained within a common lens barrel (not shown). In general, the imaging subsystem 3B" comprises: a first group of focal lens elements 3A1 mounted stationary relative to

the image detecting array 3A; a second group of lens elements 3B2, functioning as a focal lens assembly, movably mounted along the optical bench in front of the first group of stationary lens elements 3A; and a third group of lens elements 3B1, functioning as a zoom lens assembly, movably mounted between the second group of focal lens elements and the first group of stationary focal lens elements 3B2. In a non-customized application, focal distance control can also be provided by moving the second group of focal lens elements 3B2 back and forth with translator 3C2 in response to a first set of control signals 3E2 generated by the camera control computer 22, while the 1-D image detecting array 3A remains stationary. Alternatively, focal distance control can be provided by moving the 1-D image detecting array 3A back and forth along the optical axis with translator 3C2 in response to a first set of control signals 3E2 generated by the camera control computer 22, while the second group of focal lens elements 3B2 remain stationary. For zoom control (i.e. variable focal length control), the focal lens elements in the third group 3B1 are typically moved relative to each other with translator 3C1 in response to a second set of control signals 3E1 generated by the camera control computer 22. Regardless of the approach taken in any particular illustrative embodiment, an IFD module 3" with variable focus variable focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

Detailed Description Of An Exemplary Realization Of The PLIIM System Shown In Fig. 3E1 through 3E3

Referring now to Figs. 3E4 through 3E8, an exemplary realization of the PLIIM system 50B shown in Figs. 3E1 through 3E3 will now be described in detail below.

As shown in Figs. 3E41 and 3E5, an exemplary realization of the PLIIM system 50B Figs. 3E1-3E3 is indicated by reference numeral 25' contained within a compact housing 2 having height, length and width dimensions of about 4.5'', 21.7" and 19.7'', respectively, to enable easy mounting above a conveyor belt structure or the like. As shown in Fig. 3E4, 3E5 and 3E6, the PLIIM system comprises a linear image formation and detection module 3", a pair of planar laser illumination arrays 6A, and 6B, and a field of view (FOV) folding structure (e.g. mirror, refractive element, or diffractive element) 9. The function of the FOV folding mirror 9 is to fold the field of view (FOV) 10 of the image formation and detection module 3' in an imaging direction that is coplanar with the plane of laser illumination beams 7A and 7B produced by the planar illumination arrays 6A and 6B. As shown, these components are fixedly mounted to an optical bench 8 supported within the compact housing 2 so that these optical components are forced to oscillate together. The linear CCD imaging array 3A can be realized using a variety of commercially available high-speed line-scan camera systems such as, for example, the Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com. Notably, image frame grabber 19, image data buffer (e.g. VRAM) 20, image processing computer 21, and camera control computer 22 are realized on one

or more printed circuit (PC) boards contained within a camera and system electronic module 27 also mounted on the optical bench, or elsewhere in the system housing 2.

While this system design requires additional optical surfaces (i.e. planar laser beam folding mirrors) which complicates laser-beam/FOV alignment, and attenuates slightly the intensity of collected laser return light, this system design will be beneficial when the FOV of the imaging subsystem cannot have a large apex angle, as defined as the angular aperture of the imaging lens (in the zoom lens assembly), due to the fact that the IFD module 3" must be mounted on the optical bench in a backed-off manner to the conveyor belt (or maximum object distance plane), and a longer focal length lens (or zoom lens with a range of longer focal lengths) is chosen.

One notable advantage of this system design is that it enables a construction having an ultra-low height profile suitable, for example, in unitary package identification and dimensioning systems of the type disclosed in Figs. 17-22, wherein the image-based bar code symbol reader needs to be installed within a compartment (or cavity) of a housing having relatively low height dimensions. Also, in this system design, there is a relatively high degree of freedom provided in where the image formation and detection module 3" can be mounted on the optical bench of the system, thus enabling the field of view (FOV) folding technique disclosed in Fig. 1L1 to be practiced in a relatively easy manner.

As shown in Fig. 3E4, the compact housing 2 has a relatively long light transmission window 28 of elongated dimensions for the projecting the FOV 10 of the image formation and detection module 3" through the housing towards a predefined region of space outside thereof, within which objects can be illuminated and imaged by the system components on the optical bench. Also, the compact housing 2 has a pair of relatively short light transmission apertures 30A and 30B, closely disposed on opposite ends of light transmission window 28, with minimal spacing therebetween, as shown in Fig. 3E4. Such spacing is to ensure that the FOV emerging from the housing 2 can spatially overlap in a coplanar manner with the substantially planar laser illumination beams projected through transmission windows 29A and 29B, as close to transmission window 28 as desired by the system designer, as shown in Figs. 3E6 and 3E7. Notably, in some applications, it is desired for such coplanar overlap between the FOV and planar laser illumination beams to occur very close to the light transmission windows 28, 29A and 29B (i.e. at short optical throw distances), but in other applications, for such coplanar overlap to occur at large optical throw distances.

In either event, each planar laser illumination array 6A and 6B is optically isolated from the FOV of the image formation and detection module 3" to increase the signal-to-noise ratio (SNR) of the system. In the preferred embodiment, such optical isolation is achieved by providing a set of opaque wall structures 30A, 30B about each planar laser illumination array, extending from the optical bench 8 to its light transmission window 29A or 29B, respectively. Such optical isolation structures prevent the image formation and detection module 3" from detecting any laser light transmitted directly from the planar laser illumination arrays 6A and 6B within the interior of the housing. Instead, the image formation and detection module 3" can

only receive planar laser illumination that has been reflected off an illuminated object, and focused through the imaging subsystem 3B" of the IFD module 3".

Notably, the linear image formation and detection module of the PLIIM system of Fig. 3E4 has an imaging subsystem 3B" with a variable focal length imaging lens, a variable focal distance, and a variable field of view. In Fig. 3E8, the spatial limits for the FOV of the image formation and detection module are shown for two different scanning conditions, namely: when imaging the tallest package moving on a conveyor belt structure; and when imaging objects having height values close to the surface of the conveyor belt structure. In a PLIIM system having a variable focal length imaging lens and a variable focusing mechanism, the PLIIM system would be capable of imaging at either of the two conditions indicated above.

In order that PLLIM-based subsystem 25' can be readily interfaced to and an integrated (e.g. embedded) within various types of computer-based systems, as shown in Figs. 9 through 34C, subsystem 25' also comprises an I/0 subsystem 500 operably connected to camera control computer 22 and image processing computer 21, and a network controller 501 for enabling high-speed data communication with others computers in a local or wide area network using packet-based networking protocols (e.g. Ethernet, AppleTalk, etc.) well known in the art.

Third Illustrative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 3A

The third illustrative embodiment of the PLIIM system of Fig. 3A 50C is shown in Fig. 3F1 comprising: an image formation and detection module 3" having an imaging subsystem 3B" with a variable focal length imaging lens, a variable focal distance and a variable field of view, and a linear array of photo-electronic detectors 3A realized using CCD technology (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem 3B"; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams 7A and 7B, respectively; and a pair of planar laser beam folding mirrors 37A and 37B for folding the planes of the planar laser illumination beams produced by the pair of planar illumination arrays 6A and 6B, in a direction that is coplanar with the plane of the FOV of the image formation and detection module 3" during object illumination and imaging operations.

One notable disadvantage of this system architecture is that it requires additional optical surfaces (i.e. the planar laser beam folding mirrors) which reduce outgoing laser light and therefore the return laser light slightly. Also this system design requires a more complicated beam/FOV adjustment scheme than the direct-viewing design shown in Fig. 3B1. Thus, this system design can be best used when the planar laser illumination beams do not have large apex angles to provide sufficiently uniform illumination. Notably, in this system embodiment, the PLIMs are mounted on the optical bench as far back as possible from the beam folding mirrors

37A and 37B, and cylindrical lenses 16 with larger radiuses will be employed in the design of each PLIM 11A through 11P.

As shown in Fig. 3F2, the PLIIM system of Fig. 3F1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18; linear-type image formation and detection module 3A;; a pair of planar laser illumination beam folding mirrors 37A and 37B, for folding the planar laser illumination beams 7A and 7B in the imaging direction; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3", for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 3F3 illustrates in greater detail the structure of the IFD module 3" used in the PLIIM system of Fig. 3F1. As shown, the IFD module 3" comprises a variable focus variable focal length imaging subsystem 3B" and a 1-D image detecting array 3A mounted along an optical bench 3D contained within a common lens barrel (not shown). In general, the imaging subsystem 3B' comprises: a first group of focal lens elements 3A' mounted stationary relative to the image detecting array 3A; a second group of lens elements 3B2 , functioning as a focal lens assembly, movably mounted along the optical bench 3D in front of the first group of stationary lens elements 3A1; and a third group of lens elements 3B1, functioning as a zoom lens assembly, movably mounted between the second group of focal lens elements and the first group of stationary focal lens elements 3A1. In a non-customized application, focal distance control can also be provided by moving the second group of focal lens elements 3B2 back and forth in response to a first set of control signals generated by the camera control computer, while the 1-D image detecting array 3A remains stationary. Alternatively, focal distance control can be provided by moving the 1-D image detecting array 3A back and forth along the optical axis with translator in response to a first set of control signals 3E2 generated by the camera control computer 22, while the second group of focal lens elements 3B2 remain stationary. For zoom control (i.e. variable focal length control), the focal lens elements in the third group 3B1 are typically moved relative to each other with translator 3C1 in response to a second set of control signals 3E1 generated by the camera control computer 22. Regardless of the approach taken in any particular illustrative embodiment, an IFD module with variable focus variable focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

Fourth Illustrative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 3A

The fourth illustrative embodiment of the PLIIM system of Fig. 3A 50D is shown in Fig. 3G1 comprising: an image formation and detection module 3" having an imaging subsystem 3B" with a variable focal length imaging lens, a variable focal distance and a variable field of view, and a linear array of photo-electronic detectors 3A realized using CCD technology (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem 3B"; a FOV folding mirror 9 for folding the FOV of the imaging subsystem in the direction of imaging; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams 7A, 7B; and a pair of planar laser beam folding mirrors 37A and 37B for folding the planes of the planar laser illumination beams produced by the pair of planar illumination arrays 6A and 6B, in a direction that is coplanar with the plane of the FOV of the image formation and detection module during object illumination and image detection operations.

As shown in Fig. 3G2, the PLIIM system of Fig. 3G1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18; linear-type image formation and detection module 3"; a FOV folding mirror 9 for folding the FOV of the imaging subsystem in the direction of imaging; a pair of planar laser illumination beam folding mirrors 37A and 37B, for folding the planar laser illumination beams 7A and7B in the imaging direction; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3", for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer 20; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 3G3 illustrates in greater detail the structure of the IFD module 3" used in the PLIIM system of Fig. 3G1. As shown, the IFD module 3" comprises a variable focus variable focal length imaging subsystem 3B" and a 1-D image detecting array 3A mounted along an optical bench 3D contained within a common lens barrel (not shown). In general, the imaging subsystem 3B' comprises: a first group of focal lens elements 3A1 mounted stationary relative to the image detecting array 3A; a second group of lens elements 3B2, functioning as a focal lens assembly, movably mounted along the optical bench in front of the first group of stationary lens elements 3A1; and a third group of lens elements 3B1, functioning as a zoom lens assembly, movably mounted between the second group of focal lens elements and the first group of

stationary focal lens elements 3A1. In a non-customized application, focal distance control can also be provided by moving the second group of focal lens elements 3B2 back and forth with translator 3C2 in response to a first set of control signals 3E2 generated by the camera control computer 22, while the 1-D image detecting array 3A remains stationary. Alternatively, focal distance control can be provided by moving the 1-D image detecting array 3A back and forth along the optical axis in response to a first set of control signals 3E2 generated by the camera control computer 22, while the second group of focal lens elements 3B2 remain stationary. For zoom control (i.e. variable focal length control), the focal lens elements in the third group 3B1 are typically moved relative to each other with translator 3C1 in response to a second set of control signals 3C1 generated by the camera control computer 22. Regardless of the approach taken in any particular illustrative embodiment, an IFD module with variable focus variable focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

Applications For The Fifth Generalized Embodiment Of The PLIIM System Of The Present Invention, and the Illustrative Embodiments Thereof

As the PLIIM systems shown in Figs. 3A through 3G3 employ an IFD module having a linear image detecting array and an imaging subsystem having variable focal length (zoom) and variable focus (i.e. focal distance) control mechanisms, such PLIIM systems are good candidates for use in the conveyor top scanner application shown in Fig. 3H, as variations in target object distance can be up to a meter or more (from the imaging subsystem) and the imaging subsystem provided therein can easily accommodate such object distance parameter variations during object illumination and imaging operations. Also, by adding dynamic focusing functionality to the imaging subsystem of any of the embodiments shown in Figs. 3A through 3F3, the resulting PLIIM system will become appropriate for the conveyor side scanning application also shown in Fig. 3G, where the demands on the depth of field and variable focus or dynamic focus requirements are greater compared to a conveyor top scanner application.

Sixth Generalized Embodiment Of The Planar Laser Illumination And Electronic Imaging System Of The Present Invention

The sixth generalized embodiment of the PLIIM system of Fig. 3A 50' is illustrated in Figs. 3J1 and 3J2. As shown in Fig. 3J1, the PLIIM system 50' comprises: a housing 2 of compact construction; a linear (i.e. 1-dimensional) type image formation and detection (IFD) module 3"; and a pair of planar laser illumination arrays (PLIAs) 6A and 6B mounted on opposite sides of the IFD module 3". During system operation, laser illumination arrays 6A and 6B each produce a composite laser illumination beam 12 which synchronously moves and is disposed substantially coplanar with the field of view (FOV) of the image formation and

detection module 3", so as to scan a bar code symbol or other graphical structure 4 disposed stationary within a 2-D scanning region.

As shown in Figs. 3J2 and 3J3, the PLIIM system of Fig. 3J1 50' comprises: an image formation and detection module 3" having an imaging subsystem 3B" with a variable focal length imaging lens, a variable focal distance and a variable field of view, and a linear array of photo-electronic detectors 3A realized using CCD technology (e.g. Piranha Model Nos. CT-P4, or CL-P4 High-Speed CCD Line Scan Camera, from Dalsa, Inc. USA—http://www.dalsa.com) for detecting 1-D line images formed thereon by the imaging subsystem 3B"; a field of view folding and sweeping mirror 9' for folding and sweeping the field of view of the image formation and detection module 3"; a pair of planar laser illumination arrays 6A and 6B for producing planar laser illumination beams 7A and 7B; a pair of planar laser illumination beam folding and sweeping mirrors 37A' and 37B' for folding and sweeping the planar laser illumination beams 7A and 7B, respectively, in synchronism with the FOV being swept by the FOV folding and sweeping mirror 9'; an image frame grabber 19 operably connected to the linear-type image formation and detection module 3A, for accessing 1-D images (i.e. 1-D digital image data sets) therefrom and building a 2-D digital image of the object being illuminated by the planar laser illumination arrays 6A and 6B; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

As shown in Fig. 3J3, each planar laser illumination module 11A through 11F is driven by a VLD driver circuit 18 under the camera control computer 22 in a manner well known in the art. Notably, laser illumination beam folding/sweeping mirror 37A' and 37B', and FOV folding/sweeping mirror 9' are each rotatably driven by a motor-driven mechanism 39A, 39B, and 38, respectively, operated under the control of the camera control computer 22. These three mirror elements can be synchronously moved in a number of different ways. For example, the mirrors 37A', 37B' and 9' can be jointly rotated together under the control of one or more motor-driven mechanisms, or each mirror element can be driven by a separate driven motor which are synchronously controlled to enable the planar laser illumination beams and FOV to move together during illumination and detection operations within the PLIIM system.

Fig. 3J4 illustrates in greater detail the structure of the IFD module 3" used in the PLIIM system of Fig. 3J1. As shown, the IFD module 3" comprises a variable focus variable focal length imaging subsystem 3B' and a 1-D image detecting array 3A mounted along an optical bench 3D contained within a common lens barrel (not shown). In general, the imaging subsystem 3B" comprises: a first group of focal lens elements 3B" mounted stationary relative to the image detecting array 3A1 a second group of lens elements 3B2, functioning as a focal lens assembly, movably mounted along the optical bench in front of the first group of stationary lens elements 3A1; and a third group of lens elements 3B1, functioning as a zoom lens assembly,

movably mounted between the second group of focal lens elements and the first group of stationary focal lens elements 3A1. In a non-customized application, focal distance control can also be provided by moving the second group of focal lens elements 3B2 back and forth in response to a first set of control signals generated by the camera control computer, while the 1-D image detecting array 3A remains stationary. Alternatively, focal distance control can be provided by moving the 1-D image detecting array 3A back and forth along the optical axis with translator 3C2 in response to a first set of control signals 3E1 generated by the camera control computer 22, while the second group of focal lens elements 3B2 remain stationary. For zoom control (i.e. variable focal length control), the focal lens elements in the third group 3B1 are typically moved relative to each other with translator 3C1 in response to a second set of control signals 3E1 generated by the camera control computer 22. Regardless of the approach taken in any particular illustrative embodiment, an IFD module with variable focus variable focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

In accordance with the present invention, the planar laser illumination arrays 6A and 6B, the linear image formation and detection module 3", the folding/sweeping FOV mirror 9', and the planar laser illumination beam folding/sweeping mirrors 37A' and 37B' employed in this generalized system embodiment, are fixedly mounted on an optical bench or chassis 8 so as to prevent any relative motion (which might be caused by vibration or temperature changes) between: (i) the image forming optics (e.g. imaging lens) within the image formation and detection module 3" and the FOV folding/sweeping mirror 9' employed therewith; and (ii) each planar laser illumination module (i.e. VLD/cylindrical lens assembly) and the planar laser illumination beam folding/sweeping mirrors 37A' and 37B' employed in this PLIIM system configuration. Preferably, the chassis assembly should provide for easy and secure alignment of all optical components employed in the planar laser illumination arrays 6A and 6B, beam folding/sweeping mirrors 37A' and 37B', the image formation and detection module 3" and FOV folding/sweeping mirror 9', as well as be easy to manufacture, service and repair. Also, this generalized PLIIM system embodiment employs the general "planar laser illumination" and "focus beam at farthest object distance (FBAFOD)" principles described above.

Applications For The Sixth Generalized Embodiment Of The PLIIM System Of The Present Invention

As the PLIIM systems shown in Figs. 3J1 through 3J4 employ (i) an IFD module having a linear image detecting array and an imaging subsystem having variable focal length (zoom) and variable focal distance control mechanisms, and also (ii) a mechanism for automatically sweeping both the planar (2-D) FOV and planar laser illumination beam through a 3-D scanning field in a raster-like pattern while maintaining the inventive principle of "laser-beam/FOV coplanarity" herein disclosed, such PLIIM systems are good candidates for use in a hand-held scanner application, shown in Fig. 3J5, and the hands-free presentation scanner application

illustrated in Fig. 3J6. As such, these embodiments of the present invention are ideally suited for use in hand-supportable and presentation-type hold-under bar code symbol reading applications shown in Figs. 3J5 and 3J6, respectively, in which raster--like ("up and down") scanning patterns can be used for reading 1-D as well as 2-D bar code symbologies such as the PDF 147 symbology. In general, the PLIM system of this generalized embodiment may have any of the housing form factors disclosed and described in Applicant's copending US Application No. 09/204,17+ filed December 3, 1998, U.S. Application No. 09/452,976 filed December 2, 1999, and WIPO Publication No. WO 00/33239 published June 8, 2000 incorporated herein by reference. The beam sweeping technology disclosed in copending Application No. 08/931,691 filed September 16, 1997, incorporated herein by reference, can be used to uniformly sweep both the planar laser illumination beam and linear FOV in a coplanar manner during illumination and imaging operations.

Seventh Generalized Embodiment Of The PLIIM System Of The Present Invention

The seventh generalized embodiment of the PLIIM system of the present invention 60 is illustrated in Fig. 4A. As shown therein, the PLIIM system 60 comprises: a housing 2 of compact construction; an area (i.e. 2-dimensional) type image formation and detection (IFD) module 55 including a 2-D electronic image detection array 55A, and an area (2-D) imaging subsystem (LIS) 55B having a fixed focal length, a fixed focal distance, and a fixed field of view (FOV), for forming a 2-D image of an illuminated object located within the fixed focal distance and FOV thereof and projected onto the 2-D image detection array 55A, so that the 2-D image detection array 55A can electronically detect the image formed thereon and automatically produce a digital image data set 5 representative of the detected image for subsequent image processing; and a pair of planar laser illumination arrays (PLIAs) 6A and 6B, each mounted on opposite sides of the IFD module 55, for producing first and second planes of laser beam illumination 7A and 7B that are folded and swept so that the planar laser illumination beams are disposed substantially coplanar with a section of the FOV of image formation and detection module 55 during object illumination and image detection operations carried out by the PLIIM system.

In accordance with the present invention, the planar laser illumination arrays 6A and 6B, the linear image formation and detection module 55, and any stationary FOV folding mirror employed in any configuration of this generalized system embodiment, are fixedly mounted on an optical bench or chassis so as to prevent any relative motion (which might be caused by vibration or temperature changes) between: (i) the image forming optics (e.g. imaging lens) within the image formation and detection module 55 and any stationary FOV folding mirror employed therewith; and (ii) each planar laser illumination module (i.e. VLD/cylindrical lens assembly) and each planar laser illumination beam folding/sweeping mirror employed in the PLIIM system configuration. Preferably, the chassis assembly should provide for easy and secure alignment of all optical components employed in the planar laser illumination arrays 6A

and 6B as well as the image formation and detection module 55, as well as be easy to manufacture, service and repair. Also, this generalized PLIIM system embodiment employs the general "planar laser illumination" and "focus beam at farthest object distance (FBAFOD)" principles described above. Various illustrative embodiments of this generalized PLIIM system will be described below.

<u>First Illustrative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 4A</u>

The first illustrative embodiment of the PLIIM system of Fig. 4A 60A is shown in Fig. 4B1 comprising: an image formation and detection module (i.e. camera) 55 having an imaging subsystem 55B with a fixed focal length imaging lens, a fixed focal distance and a fixed field of view (FOV) of three-dimensional extent, and an area (2-D) array of photo-electronic detectors 55A realized using high-speed CCD technology (e.g. the Sony ICX085AL Progressive Scan CCD Image Sensor with Square Pixels for B/W Cameras, or the Kodak KAF-4202 Series 2032(H) x 2044(V) Full-Frame CCD Image Sensor) for detecting 2-D arean images formed thereon by the imaging subsystem 55B; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams 7A and 7B; and a pair of planar laser illumination beam folding/sweeping mirrors 57A and 57B, arranged in relation to the planar laser illumination arrays 6A and 6B, respectively, such that the planar laser illumination beams 7A, 7B are folded and swept so that the planar laser illumination beams are disposed substantially coplanar with a section of the 3-D FOV 40' of image formation and detection module during object illumination and image detection operations carried out by the PLIIM system.

As shown in Fig. 4B2, the PLIIM system 60A of Fig. 4B1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18; area-type image formation and detection module 55; planar laser illumination beam folding/sweeping mirrors 57A and 57B; an image frame grabber 19 operably connected to area-type image formation and detection module 55, for accessing 2-D digital images of the object being illuminated by the planar laser illumination arrays 6A and 6B during image formation and detection operations; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

<u>Second Illustrative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 4A</u>

The second illustrative embodiment of the PLIIM system of Fig. 4A 601 is shown in Fig. 4C1 comprising: an image formation and detection module 55 having an imaging subsystem 55B with a fixed focal length imaging lens, a fixed focal distance and a fixed field of view, and an area (2-D) array of photo-electronic detectors 55A realized using CCD technology (e.g. the Sony ICX085AL Progressive Scan CCD Image Sensor with Square Pixels for B/W Cameras, or the Kodak KAF-4202 Series 2032(H) x 2044(V) Full-Frame CCD Image Sensor) for detecting 2-D line images formed thereon by the imaging subsystem 55; a FOV folding mirror 9 for folding the FOV in the imaging direction of the system; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams 7A and 7B; and a pair of planar laser illumination beam folding/sweeping mirrors 57A and 57B, arranged in relation to the planar laser illumination arrays 6A and 6B, respectively, such that the planar laser illumination beams 7A, 7B are folded and swept so that the planar laser illumination beams are disposed substantially coplanar with a section of the FOV of the image formation and detection module during object illumination and image detection operations carried out by the PLIIM system.

In general, the arean image detection array 55B employed in the PLIEM systems shown in Figs. 4A through 6F4 has multiple rows and columns of pixels arranged in a rectangular array. Therefore, arean image detection array is capable of sensing/detecting a complete 2-D image of a target object in a single exposure, and the target object may be stationary with respect to the PLIIM system. Thus, the image detection array 55D is ideally suited for use in hold-under type scanning systems However, the fact that the entire image is captured in a single exposure implies that the technique of dynamic focus cannot be used with an arean image detector.

As shown in Fig. 4C2, the PLIIM system of Fig. 4C1 comprises: planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11B, and each planar laser illumination module being driven by a VLD driver circuit 18; area-type image formation and detection module 55B; FOV folding mirror 9; planar laser illumination beam folding/sweeping mirrors 57A and 57B; an image frame grabber 19 operably connected to area-type image formation and detection module 55, for accessing 2-D digital images of the object being illuminated by the planar laser illumination arrays 6A and 6B during image formation and detection operations; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof, including synchronous driving motors 58A and 68B, in an orchestrated manner.

<u>Applications For The Seventh Generalized Embodiment Of The PLIIM System Of The Present Invention, and the Illustrative Embodiments Thereof</u>

The fixed focal distance area-type PLIIM systems shown in Figs. 4A through 4C2 are ideal for applications in which there is little variation in the object distance, such as in a 2-D hold-under scanner application as shown in Fig. 4D. A fixed focal distance PLIIM system generally takes up less space than a variable or dynamic focus model because more advanced focusing methods require more complicated optics and electronics, and additional components such as motors. For this reason, fixed focus PLIIM systems are good choices for the hands-free presentation and hand-held scanners applications illustrated in Figs. 4D and 4E, respectively, wherein space and weight are always critical characteristics. In these applications, however, the object distance can vary over a range from several to twelve or more inches, and so the designer must exercise care to ensure that the scanner's depth of field (DOF) alone will be sufficient to accommodate all possible variations in target object distance and orientation. Also, because a fixed focus imaging subsystem implies a fixed focal length imaging lens, the variation in object distance implies that the dpi resolution of acquired images will vary as well, and therefore image-based bar code symbol decode-processing techniques must address such variations in image resolution. The focal length of the imaging lens must be chosen so that the angular width of the field of view (FOV) is narrow enough that the dpi image resolution will not fall below the minimum acceptable value anywhere within the range of object distances supported by the PLIIM system.

Eighth Generalized Embodiment Of The PLIIM System Of The Present Invention

The eighth generalized embodiment of the PLIIM system of the present invention 70 is illustrated in Fig. 5A. As shown therein, the PLIIM system 70 comprises: a housing 2 of compact construction; an area (i.e. 2-dimensional) type image formation and detection (IFD) module 55' including a 2-D electronic image detection array 55A, an area (2-D) imaging subsystem (LIS) 55B' having a fixed focal length, a variable focal distance, and a fixed field of view (FOV), for forming a 2-D image of an illuminated object located within the fixed focal distance and FOV thereof and projected onto the 2-D image detection array 55A, so that the 2-D image detection array 55A can electronically detect the image formed thereon and automatically produce a digital image data set 5 representative of the detected image for subsequent image processing; and a pair of planar laser illumination arrays (PLIAs) 6A and 6B, each mounted on opposite sides of the IFD module 55', for producing first and second planes of laser beam illumination 7A and 7B such that the 3-D field of view 10' of the image formation and detection module 55' is disposed substantially coplanar with the planes of the first and second planar laser illumination beams 7A, 7B during object illumination and image detection operations carried out by the PLIIM system. While possible, this system configuration would be difficult to use when packages are moving by on a high-speed conveyor belt, as the planar laser illumination beams would have to sweep across the package very quickly to avoid blurring of the acquired images due to the motion of the package while the image is being acquired. Thus, this system configuration might be better suited for a hold-under scanning application, as illustrated in Fig.

5D, wherein a person picks up a package, holds it under the scanning system to allow the bar code to be automatically read, and then manually routes the package to its intended destination based on the result of the scan.

In accordance with the present invention, the planar laser illumination arrays 6A and 6B, the linear image formation and detection module 55', and any stationary FOV folding mirror employed in any configuration of this generalized system embodiment, are fixedly mounted on an optical bench or chassis 8 so as to prevent any relative motion (which might be caused by vibration or temperature changes) between: (i) the image forming optics (e.g. imaging lens) within the image formation and detection module 55' and any stationary FOV folding mirror employed therewith, and (ii) each planar laser illumination module (i.e. VLD/cylindrical lens assembly) 55' and each planar laser illumination beam folding/sweeping mirror employed in the PLIIM system configuration. Preferably, the chassis assembly 8 should provide for easy and secure alignment of all optical components employed in the planar laser illumination arrays 6A and 6B as well as the image formation and detection module 55', as well as be easy to manufacture, service and repair. Also, this generalized PLIIM system embodiment employs the general "planar laser illumination" and "focus beam at farthest object distance (FBAFOD)" principles described above. Various illustrative embodiments of this generalized PLIIM system will be described below.

First Illustrative Embodiment Of The PLIIM System Shown In Fig. 5A

The first illustrative embodiment of the PLIIM system of Fig. 5A, indicated by reference numeral 70A, is shown in Figs. 5B1 and 5B2 comprising: an image formation and detection module 55' having an imaging subsystem 55B' with a fixed focal length imaging lens, a variable focal distance and a fixed field of view (of 3-D spatial extent), and an area (2-D) array of photo-electronic detectors 55A realized using CCD technology (e.g. the Sony ICX085AL Progressive Scan CCD Image Sensor with Square Pixels for B/W Cameras, or the Kodak KAF-4202 Series 2032(H) x 2044(V) Full-Frame CCD Image Sensor) for detecting 2-D images formed thereon by the imaging subsystem 55B'; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams 7A and 7B; and a pair of planar laser illumination beam folding/sweeping mirrors 57A and 57B, arranged in relation to the planar laser illumination arrays 6A and 6B, respectively, such that the planar laser illumination beams are folded and swept so that the planar laser illumination beams 7A, 7B are disposed substantially coplanar with a section of the 3-D FOV (10') of the image formation and detection module 55' during object illumination and imaging operations carried out by the PLIIM system.

As shown in Fig. 5B3, PLIIM-based system 70A comprises: planar laser illumination arrays 6A and 6B each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18; area-type image formation and detection module 55'; planar laser illumination beam folding/sweeping

mirrors 57A and 57B, driven by motors 58A and 58B, respectively; a high-resolution image frame grabber 19 operably connected to area-type image formation and detection module 55A, for accessing 2-D digital images of the object being illuminated by the planar laser illumination arrays 6A and 6B during image formation and detection operations; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner. The operation of this system configuration is as follows. Images detected by the low-resolution area camera 61 are grabbed by the image frame grabber 62 and provided to the image processing computer 21 by the camera control computer 22. The image processing computer 21 automatically identifies and detects when a label containing a bar code symbol structure has moved into the 3-D scanning field, whereupon the high-resolution CCD detection array camera 55A is automatically triggered by the camera control computer 22. At this point, as the planar laser illumination beams 12' begin to sweep the 3-D scanning region, images are captured by the high-resolution array 55A and the image processing computer 21 decodes the detected bar code by a more robust bar code symbol decode software program.

Fig. 5B4 illustrates in greater detail the structure of the IFD module 55' used in the PLIIM system of Fig. 5B3. As shown, the IFD module 55' comprises a variable focus fixed focal length imaging subsystem 55B' and a 2-D image detecting array 55A mounted along an optical bench 55D contained within a common lens barrel (not shown). The imaging subsystem 55B' comprises a group of stationary lens elements 55B1' mounted along the optical bench before the image detecting array 55A, and a group of focusing lens elements 55B2' (having a fixed effective focal length) mounted along the optical bench in front of the stationary lens elements 55B1'. In a non-customized application, focal distance control can be provided by moving the 2-D image detecting array 55A back and forth along the optical axis with translator 55C in response to a first set of control signals 55E generated by the camera control computer 22, while the entire group of focal lens elements remain stationary. Alternatively, focal distance control can also be provided by moving the entire group of focal lens elements 55B2' back and forth with translator 55C in response to a first set of control signals 55E generated by the camera control computer, while the 2-D image detecting array 55A remains stationary. In customized applications, it is possible for the individual lens elements in the group of focusing lens elements 55B2' to be moved in response to control signals generated by the camera control computer 22. Regardless of the approach taken, an IFD module 55' with variable focus fixed focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

Second Illustrative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 5A

The second illustrative embodiment of the PLIIM system of Fig. 5A is shown in Figs. 5C1, 5C2 comprising: an image formation and detection module 55' having an imaging subsystem 55B' with a fixed focal length imaging lens, a variable focal distance and a fixed field of view, and an area (2-D) array of photo-electronic detectors 55A realized using CCD technology (e.g. the Sony ICX085AL Progressive Scan CCD Image Sensor with Square Pixels for B/W Cameras, or the Kodak KAF-4202 Series 2032(H) x 2044(V) Full-Frame CCD Image Sensor) for detecting 2-D line images formed thereon by the imaging subsystem 55; a FOV folding mirror 9 for folding the FOV in the imaging direction of the system; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams 7A and 7B; and a pair of planar laser illumination beam folding/sweeping mirrors 57A and 57B, arranged in relation to the planar laser illumination arrays 6A and 6B, respectively, such that the planar laser illumination beams are folded and swept so that the planar laser illumination beams are disposed substantially coplanar with a section of the FOV of the image formation and detection module 55' during object illumination and image detection operations carried out by the PLIIM system.

As shown in Fig. 5C3, the PLIIM system 70A of Fig. 5C1 is shown in slightly greater detail comprising: a low-resolution analog CCD camera 61 having (i) an imaging lens 61B having a short focal length so that the field of view (FOV) thereof is wide enough to cover the entire 3-D scanning area of the system, and its depth of field (DOF) is very large and does not require any dynamic focusing capabilities, and (ii) an area CCD image detecting array 61A for continuously detecting images of the 3-D scanning area formed by the imaging from ambient light reflected off target object in the 3-D scanning field; a low-resolution image frame grabber 62 for grabbing 2-D image frames from the 2-D image detecting array 61A at a video rate (e.g. 3- frames/second or so); planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18; area-type image formation and detection module 55'; FOV folding mirror 9; planar laser illumination beam folding/sweeping mirrors 57A and 57B, driven by motors 58A and 58B, respectively; an image frame grabber 19 operably connected to area-type image formation and detection module 55', for accessing 2-D digital images of the object being illuminated by the planar laser illumination arrays 6A and 6B during image formation and detection operations; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 5C4 illustrates in greater detail the structure of the IFD module 55' used in the PLIIM system of Fig. 5C1. As shown, the IFD module 55' comprises a variable focus fixed focal length imaging subsystem 55B' and a 2-D image detecting array 55A mounted along an

optical bench 55D contained within a common lens barrel (not shown). The imaging subsystem 55B' comprises a group of stationary lens elements 55B1 mounted along the optical bench before the image detecting array 55A, and a group of focusing lens elements 55B2 (having a fixed effective focal length) mounted along the optical bench in front of the stationary lens elements 55B1. In a non-customized application, focal distance control can be provided by moving the 2-D image detecting array 55A back and forth along the optical axis with translator 55C in response to a first set of control signals 55E generated by the camera control computer 22, while the entire group of focal lens elements 55B1 remain stationary. Alternatively, focal distance control can also be provided by moving the entire group of focal lens elements 55B2 back and forth with the translator 55C in response to a first set of control signals 55E generated by the camera control computer, while the 2-D image detecting array 55A remains stationary. In customized applications, it is possible for the individual lens elements in the group of focusing lens elements 55B2 to be moved in response to control signals generated by the camera control computer. Regardless of the approach taken, the IFD module 55B' with variable focus fixed focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

Applications For The Eighth Generalized Embodiment Of The PLIIM System Of The Present Invention, and the Illustrative Embodiments Thereof

As the PLIIM systems shown in Figs. 5A through 5C4 employ an IFD module having an arean image detecting array and an imaging subsystem having variable focus (i.e. focal distance) control, such PLIIM systems are good candidates for use in a presentation scanner application, as shown in Fig. 5D, as the variation in target object distance will typically be less than 15 or so inches from the imaging subsystem. In presentation scanner applications, the variable focus (or dynamic focus) control characteristics of such PLIIM system will be sufficient to accommodate for expected target object distance variations.

Ninth Generalized Embodiment Of The PLIIM System Of The Present Invention

The ninth generalized embodiment of the PLIIM system of the present invention 80 is illustrated in Fig. 6A. As shown therein, the PLIIM system 80 comprises: a housing 2 of compact construction; an area (i.e. 2-dimensional) type image formation and detection (IFD) module 55' including a 2-D electronic image detection array 55A, an area (2-D) imaging subsystem (LIS) 55B" having a variable focal length, a variable focal distance, and a variable field of view (FOV) of 3-D spatial extent, for forming a 1-D image of an illuminated object located within the fixed focal distance and FOV thereof and projected onto the 2-D image detection array 55A, so that the 2-D image detection array 55A can electronically detect the image formed thereon and automatically produce a digital image data set 5 representative of the detected image for subsequent image processing; and a pair of planar laser illumination arrays

(PLIAs) 6A and 6B, each mounted on opposite sides of the IFD module 55", for producing first and second planes of laser beam illumination 7A and 7B such that the field of view of the image formation and detection module 55" is disposed substantially coplanar with the planes of the first and second planar laser illumination beams during object illumination and image detection operations carried out by the PLIIM system. While possible, this system configuration would be difficult to use when packages are moving by on a high-speed conveyor belt, as the planar laser illumination beams would have to sweep across the package very quickly to avoid blurring of the acquired images due to the motion of the package while the image is being acquired. Thus, this system configuration might be better suited for a hold-under scanning application, as illustrated in Fig. 5D, wherein a person picks up a package, holds it under the scanning system to allow the bar code to be automatically read, and then manually routes the package to its intended destination based on the result of the scan.

In accordance with the present invention, the planar laser illumination arrays 6A and 6B, the linear image formation and detection module 55", and any stationary FOV folding mirror employed in any configuration of this generalized system embodiment, are fixedly mounted on an optical bench or chassis so as to prevent any relative motion (which might be caused by vibration or temperature changes) between: (i) the image forming optics (e.g. imaging lens) within the image formation and detection module 55" and any stationary FOV folding mirror employed therewith, and (ii) each planar laser illumination module (i.e. VLD/cylindrical lens assembly) and each planar laser illumination beam folding/sweeping mirror employed in the PLIIM system configuration. Preferably, the chassis assembly should provide for easy and secure alignment of all optical components employed in the planar laser illumination arrays 6A and 6B as well as the image formation and detection module 55", as well as be easy to manufacture, service and repair. Also, this generalized PLIIM system embodiment employs the general "planar laser illumination" and "focus beam at farthest object distance (FBAFOD)" principles described above. Various illustrative embodiments of this generalized PLIIM system will be described below.

First Illustrative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 6A

The first illustrative embodiment of the PLIIM system of Fig. 6A indicated by reference numeral 8A is shown in Figs. 6B1 and 6B2 comprising: an area-type image formation and detection module 55" having an imaging subsystem 55B" with a variable focal length imaging lens, a variable focal distance and a variable field of view, and an area (2-D) array of photo-electronic detectors 55A realized using CCD technology (e.g. the Sony ICX085AL Progressive Scan CCD Image Sensor with Square Pixels for B/W Cameras, or the Kodak KAF-4202 Series 2032(H) x 2044(V) Full-Frame CCD Image Sensor) for detecting 2-D line images formed thereon by the imaging subsystem 55A; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams 7A and 7B; and a pair of planar laser illumination beam folding/sweeping mirrors 57A and 57B, arranged in relation to the planar laser

illumination arrays 6A and 6B, respectively, such that the planar laser illumination beams are folded and swept so that the planar laser illumination beams are disposed substantially coplanar with a section of the FOV of image formation and detection module during object illumination and image detection operations carried out by the PLIIM system.

As shown in Fig. 6B3, the PLIIM system of Fig. 6B1 comprises: a low-resolution analog CCD camera 61 having (i) an imaging lens 61B having a short focal length so that the field of view (FOV) thereof is wide enough to cover the entire 3-D scanning area of the system, and its depth of field (DOF) is very large and does not require any dynamic focusing capabilities, and (ii) an area CCD image detecting array 61A for continuously detecting images of the 3-D scanning area formed by the imaging from ambient light reflected off target object in the 3-D scanning field; a low-resolution image frame grabber 62 for grabbing 2-D image frames from the 2-D image detecting array 61A at a video rate (e.g. 3- frames/second or so);planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18; area-type image formation and detection module 55B; planar laser illumination beam folding/sweeping mirrors 57A and 57B; an image frame grabber 19 operably connected to area-type image formation and detection module 55", for accessing 2-D digital images of the object being illuminated by the planar laser illumination arrays 6A and 6B during image formation and detection operations; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 6B4 illustrates in greater detail the structure of the IFD module 55" used in the PLIIM system of Fig. 6B31. As shown, the IFD module 55" comprises a variable focus variable focal length imaging subsystem 55B" and a 2-D image detecting array 55A mounted along an optical bench 55D contained within a common lens barrel (not shown). In general, the imaging subsystem 55B" comprises: a first group of focal lens elements 55B1 mounted stationary relative to the image detecting array 55A; a second group of lens elements 55B2, functioning as a focal lens assembly, movably mounted along the optical bench in front of the first group of stationary lens elements 55B1; and a third group of lens elements 55B3, functioning as a zoom lens assembly, movably mounted between the second group of focal lens elements 55B2 and the first group of stationary focal lens elements 55B1. In a non-customized application, focal distance control can also be provided by moving the second group of focal lens elements 55B2 back and forth with translator 55C1 in response to a first set of control signals generated by the camera control computer, while the 2-D image detecting array 55A remains stationary. Alternatively, focal distance control can be provided by moving the 2-D image detecting array 55A back and forth along the optical axis in response to a first set of control signals 55E2 generated by the camera control computer 22, while the second group of focal lens elements 55B2 remain

stationary. For zoom control (i.e. variable focal length control), the focal lens elements in the third group 55B3 are typically moved relative to each other with translator 55C2 in response to a second set of control signals 55E2 generated by the camera control computer 22. Regardless of the approach taken in any particular illustrative embodiment, an IFD module with variable focus variable focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

Second Illustrative Embodiment Of The PLIIM System Of The Present Invention Shown In Fig. 6A

The second illustrative embodiment of the PLIIM system of Fig. 6A is shown in Fig. 6C1 and 6C2 comprising: an image formation and detection module 55" having an imaging subsystem 55B" with a variable focal length imaging lens, a variable focal distance and a variable field of view, and an area (2-D) array of photo-electronic detectors 55A realized using CCD technology (e.g. the Sony ICX085AL Progressive Scan CCD Image Sensor with Square Pixels for B/W Cameras, or the Kodak KAF-4202 Series 2032(H) x 2044(V) Full-Frame CCD Image Sensor) for detecting 2-D line images formed thereon by the imaging subsystem 55B"; a FOV folding mirror 9 for folding the FOV in the imaging direction of the system; a pair of planar laser illumination arrays 6A and 6B for producing first and second planar laser illumination beams 7A and 7B; and a pair of planar laser illumination beam folding/sweeping mirrors 57A and 57B, arranged in relation to the planar laser illumination arrays 6A and 6B, respectively, such that the planar laser illumination beams are folded and swept so that the planar laser illumination beams are disposed substantially coplanar with a section of the FOV of the image formation and detection module during object illumination and image detection operations carried out by the PLIIM system.

As shown in Fig. 6C3, the PLIIM system of Figs. 6C1 and 6C2 comprises: a low-resolution analog CCD camera 61 having (i) an imaging lens 61B having a short focal length so that the field of view (FOV) thereof is wide enough to cover the entire 3-D scanning area of the system, and its depth of field (DOF) is very large and does not require any dynamic focusing capabilities, and (ii) an area CCD image detecting array 61A for continuously detecting images of the 3-D scanning area formed by the imaging from ambient light reflected off target object in the 3-D scanning field; a low-resolution image frame grabber 62 for grabbing 2-D image frames from the 2-D image detecting array 61A at a video rate (e.g. 30 frames/second or so); planar laser illumination arrays 6A and 6B, each having a plurality of planar laser illumination modules 11A through 11F, and each planar laser illumination module being driven by a VLD driver circuit 18; area-type image formation and detection module 55A; FOV folding mirror 9; planar laser illumination beam folding/sweeping mirrors 57A and 57B; a high-resolution image frame grabber 19 operably connected to area-type image formation and detection module 55" for accessing 2-D digital images of the object being illuminated by the planar laser illumination arrays 6A and 6B during image formation and detection operations; an image data buffer (e.g.

VRAM) 20 for buffering 2-D images received from the image frame grabbers 62 and 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

Fig. 6C4 illustrates in greater detail the structure of the IFD module 55" used in the PLIIM system of Fig. 6C1. As shown, the IFD module 55" comprises a variable focus variable focal length imaging subsystem 55B" and a 2-D image detecting array 55A mounted along an optical bench 55D contained within a common lens barrel (not shown). In general, the imaging subsystem 55B" comprises: a first group of focal lens elements 55B1 mounted stationary relative to the image detecting array 55A; a second group of lens elements 55B2, functioning as a focal lens assembly, movably mounted along the optical bench in front of the first group of stationary lens elements 55A1; and a third group of lens elements 55B3, functioning as a zoom lens assembly, movably mounted between the second group of focal lens elements 55B2 and the first group of stationary focal lens elements 55B1. In a non-customized application, focal distance control can also be provided by moving the second group of focal lens elements 55B2 back and forth with translator 55C1 in response to a first set of control signals 55E1 generated by the camera control computer 22, while the 2-D image detecting array 55A remains stationary. Alternatively, focal distance control can be provided by moving the 2-D image detecting array 55A back and forth along the optical axis with translator 55C1 in response to a first set of control signals 55A generated by the camera control computer 22, while the second group of focal lens elements 55B2 remain stationary. For zoom control (i.e. variable focal length control), the focal lens elements in the third group 55B3 are typically moved relative to each other with translator in response to a second set of control signals 55E2 generated by the camera control computer 22. Regardless of the approach taken in any particular illustrative embodiment, an IFD (i.e. camera) module with variable focus variable focal length imaging can be realized in a variety of ways, each being embraced by the spirit of the present invention.

Applications For The Ninth Generalized Embodiment Of The PLIIM System Of The Present Invention

As the PLIIM systems shown in Figs. 6A through 6C4 employ an IFD module having an area-type image detecting array and an imaging subsystem having variable focal length (zoom) and variable focal distance (focus) control mechanism, such PLIIM systems are good candidates for use in a presentation scanner application, as shown in Fig. 6C5, as the variation in target object distance will typically be less than 15 or so inches from the imaging subsystem. In presentation scanner applications, the variable focus (or dynamic focus) control characteristics of such PLIIM system will be sufficient to accommodate for expected target object distance variations. All digital images acquired by this PLIIM system will have substantially the same

dpi image resolution, regardless of the object's distance during illumination and imaging operations. This feature is useful in 1-D and 2-D bar code symbol reading applications.

Exemplary Realization Of The PLIIM System Of The Present Invention, Wherein A Pair Of Coplanar Laser Illumination Beams Are Controllably Steered About A 3-D Scanning Region

In Figs. 6D1 through 6D5, there is shown an exemplary realization of the PLIIM-based system of Fig. 6A. As shown, PLIIM-based system 25'' comprises: an image formation and detection module 55'; a stationary field of view (FOV) folding mirror 9 for folding and projecting the FOV through a 3-D scanning region; a pair of planar laser illumination arrays 6A and 6B; and pair of planar laser beam folding/sweeping mirrors 57A and 57B for folding and sweeping the planar laser illumination beams so that the optical paths of these planar laser illumination beams are oriented in an imaging direction that is coplanar with a section of the field of view of the image formation and detection module 55'' as the planar laser illumination beams are swept through the 3-D scanning region during object illumination and imaging operations. As shown in Fig. 6D3, the FOV of the area-type image formation and detection module 55'' is folded by the stationary FOV folding mirror 9 and projected downwardly through a 3-D scanning region. The planar laser illumination beams produced from the planar laser illumination arrays 6A and 6B are folded and swept by mirror 57A and 57B so that the optical paths of these planar laser illumination beams are oriented in a direction that is coplanar with a section of the FOV of the image formation and detection module as the planar laser illumination beams are swept through the 3-D scanning region during object illumination and imaging operations. As shown in Fig. 6D5, PLIIM-based system 25'' is capable of auto-zoom and auto-focus operations, and producing images having constant dpi resolution regardless of whether the images are of tall packages moving on a conveyor belt structure or objects having height values close to the surface height of the conveyor belt structure.

In order that PLLIM-based subsystem 25'' can be readily interfaced to and an integrated (e.g. embedded) within various types of computer-based systems, as shown in Figs. 9 through 34C, subsystem 25'' also comprises an I/0 subsystem 500 operably connected to camera control computer 22 and image processing computer 21, and a network controller 501 for enabling high-speed data communication with others computers in a local or wide area network using packet-based networking protocols (e.g. Ethernet, AppleTalk, etc.) well know in the art.

Tenth Generalized Embodiment Of The PLIIM System Of The Present Invention, Wherein A 3-D Field Of View And A Pair Of Planar Laser Illumination Beams Are Controllably Steered About A 3-D Scanning Region

Referring to Figs. 6E1 through 6E4, the tenth generalized embodiment of the PLIIM system of the present invention 90 will now be described, wherein a 3-D field of view 101 and a

pair of planar laser illumination beams are controllably steered about a 3-D scanning region in order to achieve a greater region of scan coverage.

As shown in Fig. 6E2, PLIIM system of Fig. 6E1 comprises: an area-type image formation and detection module 55'; a pair of planar laser illumination arrays 6A and 6B; a pair of x and y axis field of view (FOV) sweeping mirrors 91A and 91B, driven by motors 92A and 92B, respectively, and arranged in relation to the image formation and detection module 55"; a pair of x and y axis planar laser illumination beam folding and sweeping mirrors 93A and 93B, driven by motors 94 and 94B, respectively, and a pair of x and y planar laser illumination beam folding and sweeping mirrors 95A and 95B, driven by motors 96A and 96B, respectively, and wherein mirrors, 93A, 93B and 95A, 95B are arranged in relation to the pair of planar laser beam illumination beam arrays 65 and 66, respectively, such that the planes of the laser illumination beams 7A, 7B are coplanar with a planar section of the 3-D field of view (101) of the image formation and detection module 55" as the planar laser illumination beams and the FOV of the IFD module 55" are synchronously scanned across a 3-D region of space during object illumination and image detection operations.

As shown in Fig. 6E3, the PLIIM system of Fig. 6E2 comprises: area-type image formation and detection module 55" having an imaging subsystem 55B" with a variable focal length imaging lens, a variable focal distance and a variable field of view (FOV) of 3-D spatial extent, and an area (2-D) array of photo-electronic detectors 55A realized using CCD technology (e.g. the Sony ICX085AL Progressive Scan CCD Image Sensor with Square Pixels for B/W Cameras, or the Kodak KAF-4202 Series 2032(H) x 2044(V) Full-Frame CCD Image Sensor) for detecting 2-D images formed thereon by the imaging subsystem 55A; planar laser illumination arrays, 6A, 6B; x and y axis FOV steering mirrors 91A and 91B; x and y axis planar laser illumination beam sweeping mirrors 93A and 93B, and 95A and 95B; an image frame grabber 19 operably connected to area-type image formation and detection module 55A, for accessing 2-D digital images of the object being illuminated by the planar laser illumination arrays 6A and 6B during image formation and detection operations; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner. Area-type image formation and detection module 55" can be realized using a variety of commercially available high-speed area-type CCD camera systems such as, for example, the KAF-4202 Series 2032(H) x 2044(V) Full-Frame CCD Image Sensor, from Eastman Kodak Company-Microelectronics Technology Division—Rochester, New York.

Fig. 6F4 illustrates a portion of the system 90 in Fig. 6E1, wherein the 3-D field of view (FOV) of the image formation and detection module 55" is shown steered over the 3-D scanning region of the system using a pair of x and y axis FOV folding mirrors 91A and 91B, which work in cooperation with the x and y axis planar laser illumination beam folding/steering mirrors 93A

and 93B and 95A and 95B to steer the pair of planar laser illumination beams 7A and 7B in a coplanar relationship with the 3-D FOV (101), in accordance with the principles of the present invention.

In accordance with the present invention, the planar laser illumination arrays 6A and 6B, the linear image formation and detection module 55", folding/sweeping FOV folding mirrors 91A and 91B, and planar laser beam illumination folding/sweeping mirrors 93A, 93B, 95A and 95B employed in this system embodiment, are mounted on an optical bench or chassis so as to prevent any relative motion (which might be caused by vibration or temperature changes) between: (i) the image forming optics (e.g. imaging lens) within the image formation and detection module 55" and FOV folding/sweeping mirrors 91A, 91B employed therewith; and (ii) each planar laser illumination module (i.e. VLD/cylindrical lens assembly) and each planar laser illumination beam folding/sweeping mirror 93A, 93B, 95A and 95B employed in the PLIIM system configuration. Preferably, the chassis assembly should provide for easy and secure alignment of all optical components employed in the planar laser illumination arrays 6A and 6B as well as the image formation and detection module 55", as well as be easy to manufacture, service and repair. Also, this PLIIM system embodiment employs the general "planar laser illumination" and "focus beam at farthest object distance (FBAFOD)" principles described above. Various illustrative embodiments of this generalized PLIIM system will be described below.

<u>First Illustrative Embodiment Of The Hybrid Holographic/CCD-Based PLIIM System Of The Present Invention</u>

In Fig. 7A, a first illustrative embodiment of the hybrid holographic/CCD-based PLIIM system of the present invention 100 is shown, wherein a holographic-based imaging subsystem is used to produce a wide range of discrete field of views (FOVs), over which the system can acquire images of target objects using a linear image detection array having a 2-D field of view (FOV) that is coplanar with a planar laser illumination beam in accordance with the principles of the present invention. In this system configuration, it is understood that the PLIIM system will be supported over a conveyor belt structure which transports packages past the PLIIM system 100 at a substantially constant velocity so that lines of scan data can be combined together to construct 2-D images upon which decode image processing algorithms can be performed.

As illustrated in Fig. 7A, the hybrid holographic/CCD-based PLIIM system 100 comprises: (i) a pair of planar laser illumination arrays 6A and 6B for generating a pair of planar laser illumination beams 7A and 7B that produce a composite planar laser illumination beam 12 for illuminating a target object residing within a 3-D scanning volume; a holographic-type cylindrical lens 101 is used to collimate the rays of the planar laser illumination beam down onto the conveyor belt surface; and a motor-driven holographic imaging disc 102, supporting a plurality of transmission-type volume holographic optical elements (HOE) 103, as taught in U.S. Patent No. 5,984,185, incorporated herein by reference. Each HOE 103 on the imaging disc 102 has a different focal length, which is disposed before a linear (1-D) CCD image detection array

3A. The holographic imaging disc 102 and image detection array 3A function as a variable-type imaging subsystem that is capable of detecting images of objects over a large range of object distances within the 3-D FOV (10") of the system while the composite planar laser illumination beam 12 illuminates the object.

As illustrated in Fig. 7A, the PLIIM system 100 further comprises: an image frame grabber 19 operably connected to linear-type image formation and detection module 3A, for accessing 1-D digital images of the object being illuminated by the planar laser illumination arrays 6A and 6B during object illumination and imaging operations; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

As shown in Fig. 7B, a coplanar relationship exists between the planar laser illumination beam(s) produced by the planar laser illumination arrays 6A and 6B, and the variable field of view (FOV) 10" produced by the variable holographic-based focal length imaging subsystem described above. The advantage of this hybrid system design is that it enables the generation of a 3-D image-based scanning volume having multiple depths of focus by virtue of the holographic-based variable focal length imaging subsystem employed in the PLIIM system.

Second Illustrative Embodiment Of The Hybrid Holographic/CCD-Based PLIIM System Of The Present Invention

In Fig. 8A, a second illustrative embodiment of the hybrid holographic/CCD-based PLIIM system of the present invention 100' is shown, wherein a holographic-based imaging subsystem is used to produce a wide range of discrete field of views (FOVs), over which the system can acquire images of target objects using an area-type image detection array having a 3-D field of view (FOV) that is coplanar with a planar laser illumination beam in accordance with the principles of the present invention. In this system configuration, it is understood that the PLIIM system 100' can used in a holder-over type scanning application, hand-held scanner application, or presentation-type scanner.

As illustrated in Fig. 8A, the hybrid holographic/CCD-based PLIIM system 101' comprises: (i) a pair of planar laser illumination arrays 6A and 6B for generating a pair of planar laser illumination beams 7A and 7B; a pair of planar laser illumination beam folding/sweeping mirrors 37A' and 37B' for folding and sweeping the planar laser illumination beams through the 3-D field of view of the imaging subsystem; a holographic-type cylindrical lens 101 for collimating the rays of the planar laser illumination beam down onto the conveyor belt surface; and a motor-driven holographic imaging disc 102, supporting a plurality of transmission-type

volume holographic optical elements (HOE) 103, as the disc is rotated about its rotational axis. Each HOE 103 on the imaging disc has a different focal length, and is disposed before an area (2-D) type CCD image detection array 55A. The holographic imaging disc 102 and image detection array 55A function as a variable-type imaging subsystem that is capable of detecting images of objects over a large range of object (i.e. working) distances within the 3-D FOV (10") of the system while the composite planar laser illumination beam 12 illuminates the object.

As illustrated in Fig. 8A, the PLIIM system 101' further comprises: an image frame grabber 19 operably connected to an area-type image formation and detection module 55", for accessing 2-D digital images of the object being illuminated by the planar laser illumination arrays 6A and 6B during object illumination and imaging operations; an image data buffer (e.g. VRAM) 20 for buffering 2-D images received from the image frame grabber 19; an image processing computer 21, operably connected to the image data buffer 20, for carrying out image processing algorithms (including bar code symbol decoding algorithms) and operators on digital images stored within the image data buffer; and a camera control computer 22 operably connected to the various components within the system for controlling the operation thereof in an orchestrated manner.

As shown in Fig. 8B, a coplanar relationship exists between the planar laser illumination beam(s) produced by the planar laser illumination arrays 6A and 6B, and the variable field of view (FOV) 10" produced by the variable holographic-based focal length imaging subsystem described above. The advantage of this hybrid system design is that it enables the generation of a 3-D image-based scanning volume having multiple depths of focus by virtue of the holographic-based variable focal length imaging subsystem employed in the PLIIM system.

<u>First Illustrative Embodiment Of The Unitary Package Identification And Dimensioning System Of The Present Invention Embodying A PLIIM Subsystem Of The Present Invention And A LADAR-Based Imaging, Detecting And Dimensioning Subsystem</u>

Referring now to Figs. 9, 10 and 11, a unitary package identification and dimensioning system of the first illustrated embodiment 120 will now be described in detail.

As shown in Fig. 10, the unitary system 120 of the present invention comprises an integration of subsystems, contained within a single housing of compact construction supported above the conveyor belt of a high-speed conveyor subsystem 121, by way of a support frame or like structure. In the illustrative embodiment, the conveyor subsystem 121 has a conveyor belt width of at least 48 inches to support one or more package transport lanes along the conveyor belt. As shown in Fig. 10, the unitary system comprises four primary subsystem components, namely: (1) a LADAR-based package imaging, detecting and dimensioning subsystem 122 capable of collecting range data from objects on the conveyor belt using a pair of multi-wavelength (i.e. containing visible and IR spectral components) laser scanning beams projected at different angular spacings as taught in copending US Application No. 09/327,756 filed June 7,

1999, supra, and International PCT Application No. PCT/US00/15624 filed June 7, 2000, incorporated herein by reference, and now published as WIPO Publication No. WO 00/75856 A1, on December 14, 2000; (2) a PLIIM-based bar code symbol reading subsystem 25', as shown in Figs. 3E4 through 3E8, for producing a scanning volume above the conveyor belt, for scanning bar codes on packages transported therealong; (3) an input/output subsystem 127 for managing the inputs to and outputs from the unitary system, including inputs from sybsystem 25'; (4) a data management computer 129 with a graphical user interface (GUI) 130, for realizing a data element queuing, handling and processing subsystem 131, as well as other data and system management functions; and (5) and a network controller 132, operably connected to the I/O subsystem 127, for connecting the system 120 to the local area network (LAN) associated with the tunnel-based system, as well as other packet-based data communication networks supporting various network protocols (e.g. Ethernet, IP, etc). Also, the network communication controller 132 enables the unitary system to receive data inputs from a number of input devices including, for example: weighing-in-motion subsystem 132, shown in Fig. 10 for weighing packages as they are transported along the conveyor belt; an RF-tag reading subsystem for reading RF tags on packages as they are transported along the conveyor belt; , an externally mounted belt tachometer for measuring the instant velocity of the belt and package transported therealong; etc. In addition, an optical filter (FO) network controller 133 may be provided for supported the Eternet or other network protocol over a filter optical cable communication medium. The advange of fiber optical cable is that it can be run thousands of feet within and about an industrial work environment while supporting high information transfer rates (required for image lift and transfer operations) without information loss. This fiber-optic data communication interface eneables the tunnel based system of Fig. 9 to be installed thousands of feet away from a keying station in a package routing hub (i.e. center), where lifted digital images and OCR (or barcode) data are simultaneously displayed on the display of a computer work station. Each bar code and/or OCR image processed by tunnel system 120 is indexed in terms of a probabilistic reliability measure, and if the measure falls below a predetermined threshold, then the lifted image and bar code and/or OCR data are simultaneously displayed for a human "key" operator to verify and correct file data, if necessary.

While a LADAR-based package imaging, detecting and dimensioning subsystem 122 is shown embodied within system 120, it is understood that other types of package imaging, detecting and dimensioning subsystems based on non-LADAR height/range data acquistion techniques (e.g. laser-illumination/CCD-imaging based triangulation techniques) may be used to realize the unitary package identification and dimensioning system of the present invention.

As shown in Fig. 10, the LADAR-based package imaging, detecting and dimensioning subsystem 122 comprises an integration of subsystems, namely: a package velocity measurement subsystem 123, for measuring the velocity of transported packages by analyzing range-based height data maps generated by the different angularly displaced AM laser scanning beams of the subsytem, using the inventive methods disclosed in International PCT Application No. PCT/US00/15624 filed December 7, 2000, supra; a package-in-the-tunnel (PITT) indication (i.e.

detection) subsystem 125, for automatically detecting the presence of each package moving through the scanning volume by reflecting a portion of one of the laser scanning beams across the width of the conveyor belt in a retro-reflective manner and then analyzing the return signal using first derivative and thresholding techniques disclosed in International PCT Application No. PCT/US00/15624 filed December 7, 2000; a package (x-y) height/width/length dimensioning (or profiling) subsystem 124, integrated within subsystem 122, for producing x,y,z profile data sets for detected packages, referenced against one or more coordinate reference systems symbolically embedded within subsystem 122, and/or unitary system 120; and a package-out-of-the-tunnel (POOT) indication (i.e. detection) subsystem 125, integrated within subsystem 122, realized using predictive techniques based on the output of the PITT indication subsystem 125, for automatically detecting the presence of packages moving out of the scanning volume.

The primary function of subsystem 122 is to measure dimensional characteristics of packages passing through the scanning volume, and produce package dimension data (i.e. a package data element) for each dimensioned package. The primary function of image-based scanning subsystem 25' is to read bar code symbols on dimensioned packages and produce package identification data (e.g. package data element) representative of each identified package. The primary function of the I/O subsystem 127 is to transport package dimension data elements and package identification data elements to the data element queuing, handling and processing subsystem 131. The primary function of the data element queuing, handling and processing subsystem 131 is to link each package dimension data element with its corresponding package identification data element, and to transport such data element pairs to an appropriate host system for subsequent use (e.g. package routing subsystems, cost-recovery subsystems, etc.). By embodying subsystem 25' and LDIP subsystem 122 within a single housing 121, an ultra-compact device is provided that can dimension, identify and track packages moving along the package conveyor without requiring the use of any external peripheral input devices, such as tachometers, light-curtains, etc.

In Fig. 11, the subsystem architecture of unitary PLIIM-based package dimensioning and identification system 140 is schematically illustrated in greater detail. As shown, various information signals (e.g., Velocity(t), Intensity(t), Height(t), Width(t), Length(t)) are automatically generated by LDIP subsystem 122 and provided to the camera control computer (subsystem) 22 embodied within PLIIM-based subsystem 25'. Notably, the Intensity(t) data signal generated from LDIP subsystem 122 represents the magnitude component of the polar-coordinate referenced range-map data stream, and specifies the "surface reflectivity" characteristics of the scanned package. The function of the camera control computer 22 generates digital camera control signals which are provided to the IFD subsystem (i.e. " variable zoom/focus camera") 3'' so that subsystem 25' can carry out its diverse functions in an integrated manner, including, but not limited to: (1) automatically capturing digital images having (i) square pixels (i.e. 1:1 aspect ratio) independent of package height or velocity, (ii) significantly reduced speckle-noise levels, and (iii) constant image resolution measured in dots per inch (DPI) independent of package height or velocity and without the use of costly

telecentric optics employed by prior art systems; (2) automatically cropping captured digital images so that digital data concerning only "regions of interest" reflecting the spatial boundaries of a package wall surface or a package label are transmitted to the image processing computer 21 for (i) image-based bar code symbol decode-processing, and/or (ii) OCR-based image processing; and (3) automatic digital image lifting operations for supporting other package management operations carried out by the end-user.

During system operation, the PLIIM-based subsystem 25' automatically generates and buffers digital images of target objects passing within the field of view (FOV) thereof. These images, image croping indices, and possibly cropped image components, are then transmitted to image processing computer 21 for decode-processing and generation of package identification data representative of decoded bar code symbols on the scanned packages. Each such package identification data element is then provided to data management computer 129 via I/O subsystem 127 (as shown in Fig. 10) for linking with a corresponding package dimension data element, as described in hereinabove. Optionally, the digital images of packages passing beneath the PLIIM subsystem 25' can be acquired (i.e. lifted) and processed by image processing computer 21 in diverse ways (e.g. using OCR programs) to extract other relevant features of the package (e.g. identity of sender, origination address, identity of recipient, destination address, etc.) which might be useful in package identification, tracking, routing and/or dimensioning operations. Details regarding the cooperation of the LDIP subsystem 122, the camera control computer 22, the IFD Subsystem 3'' and the image processing computer 21 will be described herein after with reference to Figs. 20 through 29.

In Figs. 12A and 12B, the physical construction and packaging of unitary system 120 is shown in greater detail. As shown, PLIIM-based subsystem 25' of Figs. 3E1-3E8 and LDIP subsystem 122 are contained within specially-designed, dual-compartment system housing design 161 shown in Figs. 12A and 12B to be described in detail below.

As shown in Fig. 12A, the PLIIM subsystem 25' is mounted within a first optically-isolated compartment 162 formed in system housing 161 using optically opaque wall structures, whereas the LDIP subsystem 122 and associated beam folding mirror 163 are mounted within a second optically isolated compartment 164 formed therein below the first compartment 162. Both optically isolated compartments are realized using optically opaque wall structures well known in the art. As shown in Fig. 12A, a first set of spatially registered light transmission apertures 165A1, 165A2 and 165A3 are formed through the bottom panel of the first compartment 162, in spatial registration with the light transmission apertures 29A', 28', 29B' formed in subsystem 25'. Below light transmission apertures 165A1, 165A2 and 165A3, there is formed a completely opened light transmission aperture 165B, defined by vertices EFBC, which permits laser light to exit and enter the first compartment 162 during system operation. A hingedly connected panel 169 is provided on the side opening of the system housing 161, defined by vertices ABCD. The function of this hinged panel 169 is to enable authorized personnel to access the interior of the housing and clean the glass windows provided over the light transmission apertures 29A', 28', 29B' in spatial registration with apertures 165A1, 165A2 and

165A3, respectively. This is an important consideration in most industrial scanning environments.

As shown in Figs. 12B, the LDIP subsystem 122 is mounted within the second compartment 164, along with beam folding mirror 163 directed towards a second light transmission aperture 166 formed in the bottom panel of the second compartment 164, in an optically isolated manner from the first set of light transmission apertures 165A1, 165A2 and 165A3. The function of the beam folding mirror 163 is to enable the LDIP subsystem 122 to project its dual, angularly-spaced amplitude-modulated (AM) laser beams 167 out of its housing, off beam folding mirror 163, and towards a target object to be dimensioned and profiled in accordance with the principles of invention detailed in copending US Application No. 09/327,756 filed June 7, 1999, supra, and International PCT Application No. PCT/US00/15624, supra. Also, this light transmission aperture 166 enables reflected laser return light to be collected and detected off the illuminated target object.

As shown in Fig. 12C, various optical and electro-optical components associated with the unitary package dimensioning and identification system of Fig. 9 are mounted on a first optical bench 510 that is installed within the first optically-isolated cavity 162 of the system housing. As shown, these components include: the camera subsystem 3", its variable zoom and focus lens assembly, electric motors for driving the linear lens transport carriages associated with this subsystem, and the microcomputer for realizing the camera control computer 22; camera FOV folding mirror 9, power supplies; VLD racks 6A and 6B associated with the PLIAs of the system; microcomputer 512 for the LDIP subsystem; the microcomputer for realizing the camera control computer 22 and image processing computer 21; connectors, and the like.

As shown in Fig. 12D, various optical and electro-optical components associated with the unitary package dimensioning and identification system of Fig. 9 are mounted on a second optical bench 520 that is installed within the second optically-isolated cavity 164 of the system housing. As shown, these components include, for the LDIP subsystem 122: a pair of VLDs 521A and 521B for producing a pair of AM laser beams 167A and 167B for use by the subsystem; a motor-driven rotating polygon structure 522 for sweeping the pair of AM laser beams across the rotating polygon 522; a beam folding mirror 167 for folding the swept AM laser beams and directing the same out into the scanning field of the subsystem at different scanning angles, so enable the scanning of packages and other objects within its scanning field via AM laser beams 167; a first collector mirror 523 for collecting AM laser light reflected off a package scanned by the first AM laser beam, and first light focusing lens 524 for focusing this collected laser light to a first focal point; a first avalanche-type photo-detector 525 for detecting received laser light focused to the first focal point, and generating a first electrical signal corresponding to the received AM laser beam detected by the first avalanche-type photo-detector 525; a second collector mirror 526 for collecting AM laser light reflected off the package scanned by the second AM laser beam, and a second light focusing lens 527 for focusing collected laser light to a second focal point; a second avalanche-type photo-detector 528 for detecting received laser light focused to the second focal point, and generating a second

electrical signal corresponding to the received AM laser beam detected by the second avalanche-type photo-detector 528; and a microcontroller and storage memory (e.g. hard-drive) 529, which in cooperation with LDIP computer 512, provides the computing platform used in the LDIP subsystem for carrying out the image processing, detection and dimensioning operations performed thereby. For further details concerning the LDIP subsystem 122, reference should be made to copending US Application No. 09/327,756 filed June 7, 1999, supra, and International PCT Application No. PCT/US00/15624, supra.

As shown in Fig. 12E, the IFD subsystem 3" employed in unitary system 120 comprises: a stationary lens system 530 mounted before the stationary linear (CCD-type) image detection array 3A; a first movable lens system 531 for stepped movement relative to the stationary lens system during image zooming operations; and a second movable lens system 532 for stepped movements relative to the first movable lens system 531 and the stationary lens system 530 during image focusing operations. Notably, such variable zoom and focus capabilities that are driven by lens group translators 533 and 534, respectively, operate under the control of the camera control computer 22 in response to package height, length, width, velocity and range intensity information produced in real-time by the LDIP subsystem 122. The IFD (i.e. camera) subsystem 3" of the illustrative embodiment will be described in greater detail hereinafter with reference to the tables and graphs shown in Fig. 21, 22 and 23.

In Fig. 13A, there is shown an alternative system housing design 540 for use with the unitary package identification and dimensioning subsystem of the present invention. As shown, the housing 540 has the same light transmission apertures of the housing design shown in Figs. 12A and 12B, but has no housing panels disposed about the light transmission apertures 541A, 541B and 542, through which planar laser illumination beams (PLIBs) and the field of view (FOV) of the PLIIM-based subsystem extend, respectively. This feature of the present invention provides a region of space (i.e. housing recess) into which an optional device (not shown) can be mounted for carrying out a speckle-noise reduction solution within a compact box that fits within said housing recess, in accordance with the principles of the present invention. Light transmission aperture 543 enables the AM laser beams 167 from the LDIP subsystem 122 to project out from the housing. Figs. 13B and 13C provide different perspective views of this alternative housing design.

In Fig. 14, the system architecture of the unitary (PLIIM-based) package dimensioning and identification system 120 is shown in greater detail. As shown therein, the LDIP subsystem 122 comprises: a Real-Time Package Height Profiling And Edge Detection Processing Module 450; and an LDIP Package Dimensioner 551 provided with an integrated package velocity deletion module that computes the velocity of transported packages based on package range (i.e. height) data maps produced by the front end of the LDIP subsystem 122, as taught in greater detail in copending US Application No. US Application No. 09/327,756 filed June 7, 1999, and International Application No. PCT/US00/15624, filed June 7, 2000, published by WIPO on December 14, 2000 under WIPO No. WO 00/75856 incorporated herein by reference in its entirety. The function of Real-Time Package Height Profiling And Edge Detection Processing

Module 550 is to automatically process raw data received by the LDIP subsystem 122 and generate, as output, time-stamped data sets that are transmitted to the camera control computer 22. In turn, the camera control computer 22 automatically processes the received time-stamped data sets and generates real-time camera control signals that drive the focus and zoom lens group translators within a high-speed auto-focus/auto-zoom digital camera subsystem (i.e. the IFD module) 3'' so that the image image grabber 19 employed therein automatically captures digital images having (1) square pixels (i.e. 1:1 aspect ratio) independent of package height or velocity, (2) significantly reduced speckle-noise levels, and (3) constant image resolution measured in dots per inch (dpi) independent of package height or velocity. These images are then provided to the image processing computer 21 for various types of image processing described in detail hereinabove.

Fig. 15 sets forth a flow chart describing the primary data processing operations that are carried out by the Real-Time Package Height Profiling And Edge Detection Processing Module 550 within LDIP subsystem 122 employed in the PLIIM-based system 120.

As illustrated at Block A in Fig. 15, a row of raw range data collected by the LDIP subsystem is sampled every 5 milliseconds, and time-stamped when received by the Real-Time Package Height Profiling And Edge Detection Processing Module.

As indicated at Block B, the Real-Time Package Height Profiling And Edge Detection Processing Module converts the raw data set into range profile data R=f(int. phase), referenced with respect to a polar coordinate system symbolically embedded in the LDIP subsystem 122, as shown in Fig. 17.

At Block C, the Real-Time Package Height Profiling And Edge Detection Processing Module 520 uses geometric transformations (described at Block C) to convert the range profile data set R[i] into a height profile data set h[i] and a position data set x[i].

At Block D, the Real-Time Package Height Profiling And Edge Detection Processing Module obtains current package height data values by finding the prevailing height using package edge detection without filtering, as taught in the method of Fig. 16.

At Block E, the Real-Time Package Height Profiling And Edge Detection Processing Module finds the coordinates of the left and right package edges (LPE, RPE) by searching for the closest coordinates from the edges of the conveyor belt (X_a, X_b) towards the center thereof.

At Block F, the Real-Time Package Height Profiling And Edge Detection Processing Module analyzes the data values {R(nT)} and determines the X coordinate position range $X_{\Delta 1}$, $X_{\Delta 2}$ (measured in R global) where the range intensity changes (i) within the spatial bounds (X_{LPE}, X_{RPE}), and (ii) beyond predetermined range intensity data thresholds.

At Block G in Fig. 15, the Real-Time Package Height Profiling And Edge Detection Processing Module 520 creates a time-stamped data set {X_{LPE}, h, X_{RPE}, V_B, nT} by assembling the following six (6) information elements, namely: the coordinate of the left package edge (LPE); the current height value of the package (h); the coordinate of the right package edge (RPE); X coordinate subrange where height values exhibit maximum intensity changes and the height values within said subrange; package velocity (V_b); and the time-stamp (nT). Notably, the

belt/package velocity measure V_b is computed by the LDIP Package Dimensioner __ within LDIP Subsystem 122, and employs integrated velocity detection techniques described in copending US Application No. US Application No. 09/327,756 filed June 7, 1999, and International Application No. PCT/US00/15624, filed June 7, 2000, published by WIPO on December 14, 2000 under WIPO No. WO 00/75856 incorporated herein by reference in its entirety.

Thereafter, at Block H in Fig. 15, the Real-Time Package Height Profiling And Edge Detection Processing Module 520 transmits the assembled (hextuple) data set to the camera control computer 22 for processing and subsequent generation of real-time camera control signals that are transmitted to the Auto-Focus/Auto-Zoom Digital Camera Subsystem 3''. These operation will be described in greater detail hereinafter.

Fig. 16 sets forth a flow chart describing the primary data processing operations that are carried out by the Real-Time Package Edge Detection Processing Method performed by the Real-Time Package Height Profiling And Edge Detection Processing Module at Block D in Fig. 15. This routine is carried out each time a new raw range data set is received by the Real-Time Package Height Profiling And Edge Detection Processing Module, which occurs at a rate of about every 5 milliseconds or so in the illustrative embodiment.

As shown at Block A in Fig. 16, this module commences by setting (i) the default value for x coordinate of the left package edge X_{LPE} equal to the x coordinate of the left edge pixel of the conveyor belt, and (ii) the default pixel index i equal to location of left edge pixel of the conveyor belt I_a. As indicated at Block B, the module sets (i) the default value for the x coordinate of the right package edge X_{RPE} equal to the x coordinate of the right edge pixel of the conveyor belt I_b, and (ii) the default pixel index i equal to the location of the right edge pixel of the conveyor belt I_b.

At Block C in Fig. 16, the module determines whether the search for left edge of the package reached the right edge of the belt (I_b) minus the search (i.e. detection) window size WIN. Notably, the size of the WIN parameter is set on the basis of the noise level present within the captured image data.

At Block D in Fig. 16, the module verifies whether the pixels within the search window satisfy the height threshold parameter, Hthres. In the illustrative embodiment, the height threshold parameter Hthres is set on the basis of a percentage of the expected package height of the packages, although it is understood that more complex height thresholding techniques can be used to improve performance of the method, as may be required by particular applications.

At Block E in Fig. 16, the module verifies whether the pixels within the search window are located to the right of the left belt edge.

At Block F in Fig. 16, the module slides the search window 1 pixel location to the right.

At Block G in Fig. 16, the module sets: (1) the x-coordinate of the left edge of the package to equal the x-coordinate of the left most pixel in the search window WIN; (2) the default x-coordinate of the package's right edge equal to the x-coordinate of the belt's right edge; and (3)

the default pixel location of the package's right edge equal to the pixel location of the belt's right edge.

At Block H in Fig. 16, the module verifies whether the search for right package edge reached the left edge of the belt, minus the size of the search window WIN.

At Block I in Fig. 16, the module verifies whether the pixels within search window WIN satisfy the height threshold Hthres.

As Block J in Fig. 16, the module verifies whether the pixels within search window are located to the left of the belt's right edge.

At Block K in Fig. 16, the module sides the search window 1 pixel location to the left.

At Block L in Fig. 16, the module sets the RIGHT package x-coordinate to the x-coordinate of the right most pixel in the search window.

At Block M in Fig. 16, the package edge detection process is completed. The variables LPE and RPE (i.e. stored in its memory locations) contain the x coordinates of the left and right edges of the detected package. These coordinate values are returned to the process at Block D in the flow chart of Fig. 15.

Notably, the processes and operations specified in Figs. 15 and 16 are carried out for each sampled row of raw data collected by the LDIP subsystem 122, and therefore, do not rely on the results computed by the computational-based package dimensioning processes carried out in the LDIP subsystem 122, described in great detail in copending US Application No. 09/327,756 filed June 7, 1999, and incorporated herein reference in its entirety.

As will be described in greater detail hereinafter, the camera control computer 22 controls the auto-focus/auto-zoom digital camera subsystem 3'' in an intelligent manner using the real-time camera control process illustrated in Figs. 18A and 18B. A particularly important inventive feature of this camera process is that it only needs to operate on one data set at time a time, obtained from the LDIP Subsystem 122, in order to perform its complex array of functions. Referring to Figs. 18A and 18B, the real-time camera control process of the illustrative embodiment will now be described with reference to the data structures illustrated in Figs. 19 and 20 , and the data tables illustrated in Figs. 21 and 23.

Real-Time Camera Control Process Of The Present Invention

In the illustrative embodiment, the Real-time Camera Control Process 560 illustrated in Figs. 18A and 18B is carried out within the camera control computer 21 of the PLIIM-based system 120 shown in Fig. 9. It is understood, however, that this control process can be carried out within any of the PLIIM-based systems disclosed herein, wherein there is a need to perform automated real-time object detection, dimensioning and identification operations.

This Real-time Camera Control Process provides each PLIIM-based camera subsystem of the present invention with the ability to intelligently zoom in and focus upon only the surfaces of a detected object (e.g. package) which might bear object identifying and/or characterizing information that can be reliably captured and utilized by the system or network within which the

camera subsystem is installed. This inventive feature of the present invention significantly reduces the amount of image data captured by the system which does not contain relevant information. In turn, this increases the package identification performance of the camera subsystem, while using less computational resources, thereby allowing the camera subsystem to perform more efficiently and productivity.

As illustrated in Figs. 18A and 18B, the camera control process of the present invention has multiple control threads that are carried out simultaneously during each data processing cycle (i.e. each time a new data set is received from the Real-Time Package Height Profiling And Edge Detection Processing Module 550 within the LDIP subsystem 122). As illustrated in this flow chart, the data elements contained in each received data set are automatically processed within the camera control computer in the manner described in the flow chart, and at the end of each data set processing cycle, generates real-time camera control signals that drive the zoom and focus lens group translators powered by high-speed motors and quick-response linkage provided within high-speed auto-focus/auto-zoom digital camera subsystem (i.e. the IFD module) 3" so that the camera subsystem 3'' automatically captures digital images having (1) square pixels (i.e. 1:1 aspect ratio) independent of package height or velocity, (2) significantly reduced speckle-noise levels, and (3) constant image resolution measured in dots per inch (DPI) independent of package height or velocity. Details of this control process will be described below.

As indicated at Block A in Fig. 18, the camera control computer 22 receives a time-stamped hextuple data set from the LDIP subsystem 122 after each scan cycle completed by AM laser beams 167A and 167B. In the illustrative embodiment, this data set contains the following data elements: the coordinate of the left package edge (LPE); the current height value of the package (h); x coordinate subrange , and exhibit maximum intensity changes or variations (e.g. indicative of text or other graphic information markings) and the height values contained within said subrange; the coordinate of the right package edge (RPE); package velocity (V_b); and the time-stamp (nT). The data elements associated with each current data set are initially buffered in a input row (i.e. Row 1) of the Package Data Buffer illustrated in Fig. 19. Notably, the Package Data Buffer shown in Fig. 19 functions like a six column first-in-first-out (FIFO) data element queue. As shown, each data element in the raw data set is assigned a fixed column index and (variable) row index which increments as the raw data set is shifted one index unit as each new incoming raw data set is received into the Package Data Buffer. In the illustrative embodiment, the Package Data Buffer has M number of rows, sufficient in size to determine the spatial boundaries of a package scanned by the LDIP subsystem using real-time sampling techniques which will be described in detail below

At Block B in Fig. 18, the camera control computer 22 analyzes the height data in the Package Data Buffer and detects the occurrence of height discontinuities, and based on such detected height discontinuities, determines the corresponding coordinate positions of the leading package edges specified by the left-most and right-most coordinate values (LPE and RPE) contained in the data set in the Package Data Buffer at the which the detected height discontinuity occurred.

At Block C in Fig. 18A, the camera control computer 22 determines the height of the package associated with the leading package edges determined at Block B above.

At Block D in Fig. 18A, at this stage in the control process, the camera control computer 22 analyzes the height values (i.e. coordinates) buffered in the Package Data Buffer, and determines the current "median" height of the package. At this stage of the control process, numerous control "threads" are started, each carrying out a different set of control operations in the process. As indicated in the flow chart of Figs. 18A and 18B, each control thread can only continue when the necessary parameters involved in its operation have been determined (e.g. computed), and thus the control process along a given control thread must wait until all involved parameters are available before resuming its ultimate operation (e.g. computation of a particular intermediate parameter, or generation of a particular control command), before ultimately returning to the start Block A, at which point the next time-stamped data set is received from the Real-Time Package Height Profiling And Edge Detection Processing Module 550. In the illustrative embodiment, such data set input operations are carried out every 5 milliseconds, and therefore updated camera commands are generated and provided to the auto-focus/auto-zoom camera subsystem at substantially the same rate, to achieve real-time adaptive camera control performance required by demanding imaging applications.

As indicated at Blocks E, F, G H, I, A in Figs. 18A and 18B, a first control thread runs from Block D to Block A so as to reposition the focus and zoom lens groups within the auto-focus/auto-zoom digital camera subsystem each time a new data set is received from the Real-Time Package Height Profiling And Edge Detection Processing Module 550.

As indicated at Block E, the camera control computer 22 uses the Focus/Zoom Lens Group Position Lookup Table in Fig. 21 to determine the focus and zoom lens group positions based which will capture focused digital images having constant dpi resolution, independent of detected package height. This operation requires using the median height value determined at Block D, and looking up the corresponding focus and zoom lens group positions listed in the Focus/Zoom Lens Group Position Lookup Table.

At Block F, the camera control computer 22 transmits the Lens Group Movement translates the focus and zoom lens group positions determined at Block E into Lens Group Movement Commands, which are then transmitted to the lens group position translators employed in the auto-focus/auto-zoom camera subsystem (i.e. IFD Subsystem) 3''.

At Block G, the IFD Subsystem 3'' uses the Lens Group Movement Commands to move the groups of lenses to their target positions within the IFD Subsystem.

Then at Block H, the camera control computer 22 checks the resulting positions achieved by the lens group position translators, responding to the transmitted Lens Group Movement Commands. At Blocks I and J, the camera control computer 22 automatically corrects the lens group positions which are required to capture focused digital images having constant dpi resolution, independent of detected package height. As indicated at by the control loop formed by Blocks H, I, J, H, the camera control computer corrects the lens group positions until focused

images are captured with constant dpi resolution, independent of detected package height, and when so achieved, automatically returns this control thread to Block A as shown in Fig. 18A.

As indicated at Blocks D, K, L, M in Figs. 18A and 18B, a second control thread runs from Block D in order to determine and set the optimal photo-integration time period ($\Delta T_{photo\text{-}integration}$) parameter which will ensure that digital images captured by the auto-focus/auto-zoom digital camera subsystem will have pixels of a square geometry (i.e. aspect ratio of 1:1) required by typical image-based bar code symbol decode processors and OCR processors. As indicated at Block K, the camera control computer analyzes the current median height value in the Data Package Buffer, and determines the speed of the package (V_b). At Block L, the camera control computer uses the computed values of average package height, belt speed (V_b) and the Photo-Integration Time Look-Up Table of Fig. 23, to determine the photo-integration time parameter ($\Delta T_{photo\text{-}integration}$) which will ensure that digital images captured by the auto-focus/auto-zoom digital camera subsystem will have pixels of a square geometry (i.e. aspect ratio of 1:1). At Block M, the camera control computer 22 generates a digital photo-integration time control signal based on the photo-integration time parameter ($\Delta T_{photo\text{-}integration}$) found in the Photo-Integration Time Look-Up Table, and sends this control signal to the CCD image detection array employed in the auto-focus/auto-zoom digital camera subsystem (i.e. the IFD Module). Thereafter, this control thread returns to Block A as indicated in Fig. 18A.

As indicated at Blocks D, N, O, P, Q in Figs. 18A and 18B, a third control thread runs from Block D in order to determine the pixel indices (i,j) of a selected portion of a captured image which defines the "region of interest" (ROI) on a package bearing package identifying information (e.g. bar code label, textual information, graphics, etc.), and to use these pixel indices (i,j) to produce image cropping control commands which are sent to the image processing computer 21. In turn, these control commands are used by the image processing computer 21 to crop pixels in the ROI of captured images, transferred to image processing computer 21 for image-based bar code symbol decoding and/or OCR-based image processing. This ROI cropping function serves to selectively identify for image processing only those image pixels within the Camera Pixel Buffer of Fig. 20 having pixel indices (i,j) which spatially correspond to the (row,column) indices in the Package Data Buffer of Fig. 19.

As indicated at Block N, the camera control computer transforms the position of left and right package edge (LPE, RPE) coordinates (buffered in the row the Package Data Buffer at which the height value was found at Block D), from the local Cartesian coordinate reference system symbolically embedded within the LDIP subsystem shown in Fig. 17, to a global Cartesian coordinate reference system R_{global} embedded, for example, within the center of the conveyor belt structure, beneath the LDIP subsystem 122, in the illustrative embodiment. Such coordinate frame conversions can be carried out using homogeneous transformations (HG) well known in the art.

At Block O in Fig. 18A, the camera control computer detects the x coordinates of the package boundaries based on the spatially transformed coordinate values of the left and right package edges (LPE,RPE) buffered in the Package Data Buffer, shown in Fig. 19.

At Block P, the camera control computer 22 determines the corresponding pixel indices (i,j) which specifies the portion of the image frame (i.e. a slice of the region of interest), to be effectively cropped from the image to be subsequently captured by the auto-focus/auto-zoom digital camera subsystem 3". This pixel indices specification operation involves using (i) the x coordinates of the detected package boundaries determined Block O, and (ii) optionally, the subrange of x coordinates bounded within said detected package boundaries, over which maximum range "intensity" data variations have been detected by the module of Fig. 15. By using the x coordinate boundary information specified in item (i) above, the camera control computer 22 can determine which image pixels represent the overall detected package, whereas when using the x coordinate subrange information specified in item (ii) above, the camera control computer 22 can further determine which image pixels represent a bar code symbol label, hand-writing, typing, or other graphical indicia recorded on the surface of the detected package. Such additional information enables the camera control computer 22 to selectively crop only pixels representative of such information content, and inform the image processing computer 21 thereof, on a real-time scanline-by-scanline basis, thereby reducing the computational load on image processing computer 21 by use of such intelligent control operations.

Thereafter, this control thread dwells at Block R until the other control threads terminating at Block Q have been executed, providing the necessary information to complete the operation specified at Block Q, and then proceed to Block R, as shown in Fig. 18B.

As indicated at Block Q in Fig. 18B, the camera control computer uses the package time stamp (nT) contained in the data set being currently processed by the camera control computer, as well as the package velocity (V_b) determined at Block K, to determine the "Start Time" of Image Frame Capture (STIC). The reference time is established by the package time stamp (nT). The Start Time when the image frame capture should begin is measured from the reference time, and is determined by (1) predetermining the distance Δz measured between (i) the local coordinate reference frame embedded in the LDIP subsystem and (ii) the local coordinate reference frame embedded within the auto-focus/auto-zoom camera subsystem, and dividing this predetermined (constant) distance measure by the package velocity (V_b). Then at Block R, the camera control computer uses the Start Time of Image Frame Capture determined at Block Q to generate a command for starting image frame capture, and uses the pixel indices (i,j) determined at Block P to generate commands for cropping the corresponding slice (i.e. section) of the region of interest in the image to be or being captured and buffered in the Image Buffer within the IFD Subsystem (i.e. auto-focus/auto-zoom digital camera subsystem). Then at Block S, these real-time "image-cropping" commands are transmitted to the IFD Subsystem (auto-focus/auto-zoom sigital camera subsystem) 3'' and the control process returns to Block A to begin processing another incoming data set received from the Real-Time Package Height Profiling And Edge Detection Processing Module 550. This aspect of the inventive camera control process 560 effectively informs the image processing computer 21 to only process those cropped image pixels which the LDIP subsystem 122 has determined as representing graphical indicia

containing information about either the identity, origin and/or destination of the package moving along the conveyor belt.

Alternatively, camera control computer 22 can use computed RDI pixel information to crop captured images in camera control computer 22 and then transfer such cropped images to the image processing computer 21 for processing.

Also, any one of the numerous methods of and apparatus for speckle-noise reduction described in great detail hereinabove can be embodied within the unitary system 120 to provide an ultra-compact, ultra-lightweight system capable of high performance image acquistion and processing operation, undaunted by speckle-noise patterns which seriously degrade the performance of prior art systems attempting to illuminate objects using solid-state VLD devices, as taught herein.

<u>Second Illustrative Embodiment Of The Unitary Package Identification And Dimensioning System Of The Present Invention Embodying A PLIIM Subsystem Of The Present Invention And A LADAR-Based Imaging, Detecting And Dimensioning Subsystem</u>

Referring now to Figs. 24, 25, and 26, a unitary PLIIM-based package identification and dimensioning system of the second illustrated embodiment 140 will now be described in detail.

As shown in Fig. 24, the unitary PLIIM-based system 140 comprises an integration of subsystems, contained within a single housing of compact construction supported above the conveyor belt of a high-speed conveyor subsystem 121, by way of a support frame or like structure. In the illustrative embodiment, the conveyor subsystem 141 has a conveyor belt width of at least 48 inches to support one or more package transport lanes along the conveyor belt. As shown in Fig. 25, the unitary PLIIM-based system 140 comprises four primary subsystem components, namely: (1) a LADAR-based package imaging, detecting and dimensioning subsystem 122 capable of collecting range data from objects on the conveyor belt using a pair of multi-wavelength (i.e. containing visible and IR spectral components) laser scanning beams projected at different angular spacing as taught in copending US Application No. 09/327,756 filed June 7, 1999, supra, and International PCT Application No. PCT/US00/15624 filed December 7, 2000, incorporated herein by reference; (2) a PLIIM-based bar code symbol reading subsystem 25'', shown in Figs. 6D1 through 6D5, for producing a 3-D scanning volume above the conveyor belt, for scanning bar codes on packages transported therealong; (3) an input/output subsystem 127 for managing the inputs to and outputs from the unitary system; a network controller 132 for connecting to a local or wide area IP network, and support one or more networking protocols, such as, for example, Ethernet, Appletalk, etc.; a high-speed fiber optic (FO) network controller 133 for connecting the subsystem 140 to a local or wide area IP network and supporting one or more netoworking protocols such as, for example, Ethernet, Appletalk, etc.; and (4) a data management computer 129 with a graphical user interface (GUI) 130, for realizing a data element queuing, handling and processing subsystem 131, as well as other data and system management functions. As shown in Fig. 25, the package imaging,

detecting and dimensioning subsystem 122 embodied within system 140 comprises the same integration of subsystems as shown in Fig. 10, and thus warrants no further discussion. It is understood, however, that other non-ladar based package detection, imaging and dimensioning subsystems could be used to emulate the functionalities of the LDIP subsystem 122.

As shown in Fig. 25, system 140 comprises a PLIIM-based camera subsystem 25''' which includes a high-resolution 2D CCD camera subsystem 25'' similar in many ways to the subsystem shown in Figs. 6D1 through 6E3, except that the 2-D CCD camera's 3-D field of view is automatically steered over a large scanning field, as shown in Fig. 6E4, in response to FOV steering control signals automatically generated by the camera control computer 22 as a low-resolution CCD area-type camera (640x640 pixels) 61 determines the x,y position coordinates of bar code labels on scanned packages. As shown in Figs. 5B3, 5C3, 6B3, and 6C3, the components (61A, 61B and 62) associated with low-resolution CCD area-type camera 61 are easily integrated within the system architecture of PLIIM-based camera subsystems. In the illustrative embodiment, low-resolution camera 61 is controlled by a camera control process carried out within the camera control computer 22, by modifying the camera control process illustrated in Figs.18A and 18B. The major difference with this modified camera control process is that it will include subprocesses that generate FOV steering control signals, in addition to zoom and focus control signals, discussed in great detail hereinabove.

In the illustrative embodiment, when the low-resolution CCD image detection array 61A detects a bar code symbol on a package label, the camera control computer 22 automatically (i) triggers into operation a high-resolution CCD image detector 55A and the planar laser illumination arrays (PLIA) 6A and 6B operably associated therewith and (ii) generates FOV steering control signals for steering the FOV of camera subsystem 55''' and capturing 2-D images of packages within the 3-D field of view of the high-resolution image detection array 61A. The zoom and focal distance of the imaging subsystem employed in the high-resolution camera (i.e. IFD module) 55''' are automatically controlled by the camera control process running within the camera control computer 22 using, for example, package height coordinate and velocity information acquired by the LDIP subsystem 122. High-resolution image frames (i.e. scan data) captured by the 2-D image detector 55A are then provided to the image processing computer 21 for decode processing of bar code symbols on the detected package label, or OCR processing of textual information represented therein. In all other respects, the PLIIM-based system 140 shown in Fig. 24 is similar to PLIIM-based system 120 shown in Fig. 9. By embodying PLIIM-based camera subsystem 25'' and LDIP package detecting and dimensioning subsystem 122 within a single housing 141, an ultra-compact device is provided that uses a low-resolution CCD imaging device to detect package labels and dimension, identify and track packages moving along the package conveyor, and then uses such detected label information to activate a high-resolution CCD imaging device to acquire high-resolution images of the detected label for high performance decode-based image processing.

Notably, any one of the numerous methods of and apparatus for speckle-noise reduction described in great detail hereinabove can be embodied within the unitary system 140 to provide

an ultra-compact, ultra-lightweight system capable of high performance image acquistion and processing operation, undaunted by speckle-noise patterns which seriously degrade the performance of prior art systems attempting to illuminate objects using coherent radiation.

Tunnel-Type Package Identification And Dimensioning System Of The Present Invention

The PLIIM-based package identification and dimensioning systems and subsystems described hereinabove can be configured as building blocks to build more complex, more robust systems designed for diverse types of object identification and dimensioning applications. In Fig. 27, there is shown a four-sided tunnel-type package identification and dimensioning system 570 that has been constructed by arranging, about a high-speed package conveyor belt subsystem 571, four PLIIM-based package identification (PID) units 120 of the type shown in Figs. 13 through 17, and integrating these PID units within a high-speed data communications network 572 having a suitable network topology and configuration, as illustrated, for example, in Figs. 28 and 29.

In this illustrative tunnel-type system, only the top PID unit 120 includes LDIP subsystem 122, as this unit functions as a master PID unit within the tunnel system, whereas the side and bottom PID units 120 are not provided with a LDIP subsystem 122 and function as slave PID units. As such, the side and bottom PID units 120' are programmed to receive package dimension data (e.g. height, length and width coordinates) from the master PID unit 120 on a real-time basis, and automatically convert (i.e. transform) these package dimension coordinates into their local coordinate reference frames in order to use the same to dynamically control the zoom and focus parameters of the camera subsystems employed in the tunnel system. This centralized method of package dimensioning offers numerous advantages over prior art systems and will be described in greater detail with reference to Figs. 30 through 32B.

As shown in Fig. 27, the camera field of view (FOV) of the bottom PID unit 120' of the tunnel system 570 is arranged to view packages through a small gap 573 provided between conveyor belt sections 571A and 571B. Notably, this arrangement is permissible by virtue of the fact that the camera's FOV and its coplanar PLIB jointly have thickness dimensions on the order of millimeters. As shown in Fig. 28, all of the PID units in the tunnel system are operably connected to an Ethernet control hub 575 (ideally contained in one of the slave PID units) associated with a local area network (LAN) embodied within the tunnel system. As shown, an external tachometer (i.e. encoder) 576 connected to the conveyor belt 571 provides tachometer input signals to each slave unit 120 and master unit 120, as a backup to integrated velocity detector provided within the LDIP subsystem 122. This is an optional feature which may have advantages in environments where the belt speed fluctuates frequently and by significant amounts. Fig. 28 shows the tunnel system of Fig. 27 embedded within a first-type LAN having a Ethernet control hub 575, for communicating data packets to control the operation of units 120 in the LAN, but not transfer camera data (e.g. 80 megabytes/sec).

Fig. 29 shows the tunnel system of Fig. 27 embedded within a second-type LAN having a Ethernet control hub 575 and a Ethernet data switch 577, and an encoder 576. The function of the Ethernet data switch 577 is to transfer data packets relating to camera data output, whereas the functions of control hub 575 are the same as in the tunnel network system configuration of Fig. 28. The advantages of using the tunnel network configuration of Fig. 29 is that camera data can be transferred over the LAN, and when using fiber optical (FO) cable, camera data can be transferred very long distances over FO-cable using the Ethernet networking protocol (i.e. Ethernet over fiber). As discussed hereinabove, the advantage of using Ethernet over fiber optical cable is that a "keying" workstation 580 can be located thousands of feet away from the tunnel system 570 within a package routing facility, without compromising camera data integrity due to transmission loss and/or errors.

<u>Real-Time Package Coordinate Data Driven Method Of Camera Zoom And Focus Control In Accordance With The Principles Of The Present Invention</u>

In Figs. 30 through 32B, CCD camera-based tunnel system 570 of Fig. 27 is schematically illustrated employing a real-time method of automatic camera zoom and focus control in accordance with the principles of the present invention. As will be described in greater detail below, this real-time method is driven by package coordinate data and involves (i) dimensioning packages in a global coordinate reference system, (ii) producing package coordinate data referenced to said global coordinate reference system, and (iii) distributing said package coordinate data to local coordinate references frames in the system for conversion of said package coordinate data to local coordinate reference frames and subsequent use automatic camera zoom and focus control operations upon said packages. This method of the present invention will now be described in greater detail below using the four-sided tunnel-based system 570 of Fig. 27, described above.

As shown in Fig. 30, the four-sided tunnel-type camera-based package identification and dimensioning system of Fig. 27 comprises: a single master PID unit 120 embodying a LDIP subsytem 122, mounted above the conveyor belt structure 571; three slave PID units 120', 120' and 120', mounted on the sides and bottom of the conveyor belt; and a high-speed data communications network 572 supporting a network protocol such as, for example, Ethernet, and enabling high-speed packet-type data communications among the four PID units within the system. As shown, each PID unit is connected to the network communication medium of the network through its network controller 132 (133) in a manner well known in the computer networking arts.

As schematically illustrated in Figs. 30 and 31, local coordinate reference systems are symbolically embodied within each of the PID units deployed in the tunne-ltype system of Fig. 27, namely: local coordinate reference system R_{local0} symbolically embodied within the master PID unit 120; local coordinate reference system R_{local1} symbolically embodied within the first side PID unit 120'; local coordinate reference system R_{local2} symbolically embodied within the

second side PID unit 120'; and local coordinate reference system R_{local3} symbolically embodied within the bottom PID unit 120'. In turn, each of these local coordinate reference systems is "referenced" with respect to a global coordinate reference system R_{global} symbolically embodied within the conveyor belt structure. Package coordinate information specified (by vectors) in the global coordinate reference system can be readily converted to package coordinate information specified in any local coordinate reference system by way of a homogeneous transformation (HG) constructed for the global and the particular local coordinate reference system. Each homogeneous transformation can be constructed by specifying the point of origin and orientation of the x,y, z axes of the local coordinate reference system with respect to the point of origin and orientation of the x,y,z axes of the global coordinate reference system. Such details on homogeneous transformations are well known in the art.

Once the PID units have been installed within a given tunnel system, such information must be ascertained to (i) properly construct the homogeneous transformation expression between each local coordinate reference system and the global coordinate reference system, and (ii) subsequently program this mathematical construction within camera control computer 22 within each PID unit 120 (120'). Preferably, a PID unit support framework installed about the conveyor belt structure, can be used in the tunnel system to simplify installation and configuration of the PID units at particular predetermined locations and orientations required by the scanning application at hand. In accordance with such a method, the predetermined location and orientation position of each PID unit can be premarked or bar coded. Then, once a particular PID unit has been installed, the location/orientation information of the PID unit can be quickly read in the field and programmed into the camera control computer 22 of each PID unit so that its homogeneous transformation (HG) expression can be readily constructed and programmed into the camera control compute for use during tunnel system operation. Notably, a hand-held bar code symbol reader, operably connected to the master PID unit, can be used in the field to quickly and accurately collect such unit position/orientation information (e.g. by reading bar code symbols pre-encoded with unit position/orientation information) and transmit the same to the master PID unit.

In addition, Fig. 30 illustrates that the LDIP subsystem 122 within the master unit 120 generates (i) package height, width, and length coordinate data and (ii) velocity data, referenced with respect to the global coordinate reference system R_{global}. These package dimension data elements are transmitted to each slave PID unit 120' on the data communication network, and once received, its camera control computer 22 converts there values into package height, width, and length coordinates referenced to its local coordinate reference system using its preprogrammable homogeneous transformation. The camera control computer 22 in each slave PID unit 120 uses the converted package dimension coordinates to generate real-time camera control signals which automatically drive its camera's automatic zoom and focus imaging optics in an intelligent, real-time manner in accordance with the principles of the present invention. The package identification data elements generated by the slave PID unit are automatically transmitted to the master PID unit 120 for time-stamping, queuing, and processing to ensure

accurate package dimension and identification data element linking operations in accordance with the principles of the present invention.

Referring to Figs. 32A and 32B, the package-coordinate driven camera control method of the present invention will now be described in detail.

As indicated at Block A in Fig. 32A, Step A of the camera control method involves the master PID unit (with LDIP subsystem 122) generating a package dimension data element (e.g. containing height, width, length and velocity data $\{H,W,L,V\}_G$) for each package transported through tunnel system, and then using the system's data communications network, to. transmit such package dimension data to each slave PID unit downstream the conveyor belt. Preferably, the coordinate information contained in each package dimension data element is referenced with respect to global coordinate reference system R_{global}, although it is understood that the local coordinate reference frame of the master PID unit may also be used as a central coordinate reference system in accordance with the principles of the present invention.

As indicated at Block B in Fig. 32A, Step B of the camera control method involves each slave unit receiving the transmitted package height, width and length data $\{H,W,L,V\}_G$ and converting this coordinate information into the slave unit's local coordinate reference system $R_{local\ I}$, $\{H,W,L,V\}_i$.

As indicated at Block C in Fig. 32A, Step C of the camera control method involves the camera control computer in each slave unit useing the converted package height, width, length data $\{H,W,L\}_i$ and package velocity data to generate camera control signals for driving the camera subsystem in the slave unit to zoom and focus in on the transported package as it moves by the slave unit, while ensuring that captured images having substantially constant d.p.i. resolution and 1:1 aspect ratio.

As indicated at Block D in Fig. 32B, Step D of the camera control method involves each slave unit capturing images acquired by its intelligently controlled camera subsystem, buffering the same, and processing the images so as to decode bar code symbol identifiers represented in said images, and/or to perform optical character recognition (OCR) thereupon.

As indicated at Block E in Fig. 32B, Step E of the camera control method involves the slave unit, which decoded a bar code symbol in a processed image, to automatically transmit a package identification data element (containing symbol character data representative of the decoded bar code symbol) to the master unit (or other designated system control unit employing data element management functionalities) for package data element processing.

As indicated at Block F in Fig. 32B, Step F of the camera control method involves the master unit time-stamping each received package identification data element, placing said data element in a data queue, and processing package identification data elements and time-stamped package dimension data elements in said queue so as to link each package identification data element with one said corresponding package dimension data element.

The real-time camera zoom and focus control process described above has the advantage of requiring on only one package detection and dimensioning subsystem, yet enabling (i) intelligent zoom and focus control within each camera subsystem in the system, and (ii) precise cropping of

"regions of interest" in captured images. Such inventive features enable intelligent filtering and processing of image data streams and thus substantially reduce data processing requirements in the system.

Bioptical PLIIM-Based Product Dimensioning, Analysis And Identification System Of The First Illustrative Embodiment Of The Present Invention

The numerous types of PLIIM-based camera systems disclosed hereinabove can be used as stand-alone devices, as well as components within resultant systems designed to carry out particular functions.

As shown in Figs. 33A through 33C, a pair of PLIIM-based package identification (PID) systems 25' of Figs. 3E4 through 3E8 are modified and arranged within a compact POS housing 581 having bottom and side light transmission apertures 582 and 583 (beneath bottom and side imaging windows 584 and 585, respectively), to produce a bioptical PLIIM-based product identification, dimensioning and analysis (PIDA) system 580 according to a first illustrative embodiment of the present invention. As shown in Fig. 33C, the bioptical PIDA system 580 comprises: a bottom PLIIM-based unit 586A mounted within the bottom portion of the housing 581; a side PLIIM-based unit 586B mounted within the side portion of the housing 581; an electronic product weigh scale 587, mounted beneath the bottom PLIIM-based unit 587A, in a conventional manner; and a local data communication network 588, mounted within the housing, and establishing a high-speed data communication link between the bottom and side units 586A and 586B, and the electronic weigh scale 587, and a host computer system (e.g. cash register) 589.

As shown in Fig. 33C, the bottom unit 586A comprises: a PLIIM-based PIB subsystem 25' (without LDIP subsystem 122), installed within the bottom portion of the housing 587, for projecting a coplanar PLIB and 1-D FOV through the bottom light transmission aperture 582, on the side closest to the product entry side of the system indicated by the "arrow" (⇐) indicator shown in the figure drawing; a I/O subsystem 127 providing data, address and control buses, and establishing data ports for data input to and data output from the PLIIM-based PIB subsystem 25'; and a network controller 132, operably connected to the I/O subsystem 127 and the communication medium of the local data communication network 588.

As shown in Fig. 33C, the side unit 586B comprises: a PLIIM-based PID subsystem 25' (with LDIP subsystem 122), installed within the side portion of the housing 581, for projecting (i) a coplanar PLIB and 1-D FOV through the side light transmission aperture 583, also on the side closest to the product entry side of the system indicated by the "arrow" (⇐) indicator shown in the figure drawing, and also (ii) a pair of AM laser beams, angularly spaced from each other, through the side light transmission aperture 583, also on the side closest to the product entry side of the system indicated by the "arrow" (⇐) indicator shown in the figure drawing, but closer to the arrow indicator than the coplanar PLIB and 1-D FOV projected by the subsystem, thus locating them slightly downstream from the AM laser beams used for product dimensioning and

detection; a I/O subsystem 127 for establishing data ports for data input to and data output from the PLIIM-based PIB subsystem 25'; a network controller 132, operably connected to the I/O subsystem 127 and the communication medium of the local data communication network 588; and a system control computer 590, operably connected to the I/O subsystem 127, for (i) receiving package identification data elements transmitted over the local data communication network by either PLIIM-based PID subsystem 25', (ii) package dimension data elements transmitted over the local data communication network by the LDIP subsystem 122, and (iii) package weight data elements transmitted over the local data communication network by the electronic weigh scale 587. As shown, LDIP subsystem 122 includes an integrated package/object velocity measurement subsystem

In order that the bioptical PLIIM-based PIDA system 580 is capable of capturing and analyzing color images, and thus enabling, in supermarket environments, "produce recognition" on the basis of color as well as dimensions and geometrical form, each PLIIM-based subsystem 25' employs (i) a plurality of visible laser diodes (VLDs) having different color producing wavelengths to produce a multi-spectral planar laser illumination beam (PLIB) from the side and bottom light transmission apertures 582 and 583, and also (ii) a 1-D (linear-type) CCD image detection array for capturing color images of objects (e.g. produce) as the objects are manually transported past the imaging windows 584 and 585 of the bioptical system, along the direction of the indicator arrow, by the user or operator of the system (e.g. retail sales clerk).

Any one of the numerous methods of and apparatus for speckle-noise reduction described in great detail hereinabove can be embodied within the bioptical system 580 to provide an ultra-compact system capable of high performance image acquistion and processing operation, undaunted by speckle-noise patterns which seriously degrade the performance of prior art systems attempting to illuminate objects using solid-state VLD devices, as taught herein.

Notably, the image processing computer 21 within each PLIIM-based subsystem 25' is provided with robust image processing software 582 that is designed to process color images captured by the subsystem and determine the shape/geometry, dimensions and color of scanned products in diverse retail shopping environments. In the illustrative embodiment, the IFD subsystem (i.e. "camera") 3'' within the PLIIM-based subsystem 25'' is capable of: (1) capturing digital images having (i) square pixels (i.e. 1:1 aspect ratio) independent of package height or velocity, (ii) significantly reduced speckle-noise levels, and (iii) constant image resolution measured in dots per inch (DPI) independent of package height or velocity and without the use of costly telecentric optics employed by prior art systems, (2) automatic cropping of captured images so that only regions of interest reflecting the package or package label are transmitted to either an image-processing based 1-D or 2-D bar code symbol decoder or an optical character recognition (OCR) image processor, and (3) automatic image lifting operations. Such functions are carried out in substantially the same manner as taught in connection with the tunnel-based system shown in Figs. 27 through 32B.

In most POS retail environments, the sales clerk may pass either a UPC or UPC/EAN labeled product past the bioptical system, or an item of produce (e.g. vegetables, fruits, etc.). In

the case of UPC labeled products, the image processing computer 21 will decode process images captured by the IFD subsystem 3' (in conjuction with performing OCR processing for reading trademarks, brandnames, and other textual indicia) as the product is manually moved past the imaging windows of the system in the direction of the arrow indicator. For each product identified by the system, a product identification data element will be automatically generated and transmitted over the data communication network to the system control/management computer 590, for transmission to the host computer (e.g. cash register computer) 589 and use in check-out computations. Any dimension data captured by the LDIP subsystem 122 while identifying a UPC or UPC/EAN labeled product, can be disregarded in most instances; although, in some instances, it might make good sense that such information is automatically transmitted to the system control/management computer 590, for comparison with information in a product information database so as to cross-check that the identified product is in fact the same product indicated by the bar code symbol read by the image processing computer 21. This feature of the bioptical system can be used to increase the accurately of product identification, thereby lowering scan error rates and improving consumer confidence in POS technology.

In the case of an item of produce swept past the light transmission windows of the bioptical system, the image processing computer 21 will automatically process images captured by the IFD subsystem 3'' (using the robust produce identification software mentioned above), alone or in combination with produce dimension data collected by the LDIP subsystem 122. In the preferred embodiment, produce dimension data (generated by the LDIP subsystem 122) will be used in conjunction with produce identification data (generated by the image processing computer 21), in order to enable more reliable identification of produce items, prior to weigh in on the electronic weigh scale 587, mounted beneath the bottom imaging window 584. Thus, the image processing computer 21 within the side unit 586B (embodying the LDIP subsystem 122) can be designated as providing primary color images for produce recognition, and cross-correlation with produce dimension data generated by the LDIP subsystem 122. The image processing computer 21 within the bottom unit (without an LDIP subsystem) can be designated as providing secondary color images for produce recognition, independent of the analysis carried out within the side unit, and produce identification data generated by the bottom unit can be transmitted to the system control/management computer 590, for cross-correlation with produce identification and dimension data generated by the side unit containing the LDIP subsystem 122.

In alternative embodiments of the bioptical system described above, both the side and bottom units can be provided with an LDIP subsystem 122 for product/produce dimensioning operations. Also, it may be desirable to use a simpler set of image forming optics than that provided within IFD subsystem 3''. Also, it may desirable to use PLIIM-based subsystems which have FOVs that are automatically swept across a large 3-D scanning volume definable between the bottom and side imaging windows 584 and 585. The advantage of this type of system design is that the product or item of produce can be presented to the bioptical system without the need to move the product or produce item past the bioptical system along a predetermined scanning/imaging direction, as required in the illustrative system of Figs. 33A

through 33C. With this modification in mind, reference is now made to Figs. 34A through 34C in which an alternative bioptical vision-based product/produce identification system 600 is disclosed employing the PLIIM-based camera system disclosed in Figs. 6D1 through 6E3.

Bioptical PLIIM-Based Product Identification, Dimensioning and Analysis System Of The Second Illustrative Embodiment Of The Present Invention

As shown in Figs. 34A through 34C, a pair of PLIIM-based package identification (PID) systems 25'' of Figs. 6D1 through 6E3 are modified and arranged within a compact POS housing 601 having bottom and side light transmission windows 602 and 603 (beneath bottom and side imaging windows 604 and 605, respectively), to produce a bioptical PLIIM-based product identification, dimensioning and analysis (PIDA) system 600 according to a second illustrative embodiment of the present invention. As shown in Fig. 34C, the bioptical PIDA system 600 comprises: a bottom PLIIM-based unit 606A mounted within the bottom portion of the housing 601; a side PLIIM-based unit 606B mounted within the side portion of the housing 601; an electronic product weigh scale 589, mounted beneath the bottom PLIIM-based unit 606A, in a conventional manner; and a local data communication network 588, mounted within the housing, and establishing a high-speed data communication link between the bottom and side units 606A and 606B, and the electronic weigh scale 589.

As shown in Fig. 34C, the bottom unit 606A comprises: a PLIIM-based PIB subsystem 25'' (without LDIP subsystem 122), installed within the bottom portion of the housing 601, for projecting an automatically swept PLIB and a stationary 3-D FOV through the bottom light transmission window 602; a I/O subsystem 127 providing data, address and control buses, and establishing data ports for data input to and data output from the PLIIM-based PIB subsystem 25''; and a network controller 132, operably connected to the I/O subsystem 127 and the communication medium of the local data communication network 588.

As shown in Fig. 34C, the side unit 606A comprises: a PLIIM-based PID subsystem 25'' (with modified LDIP subsystem 122'), installed within the side portion of the housing 601, for projecting (i) an automatically swept PLIB and a stationary 3-D FOV through the bottom light transmission window 605, and also (ii) a pair of automatically swept AM laser beams 607A, 607B, angularly spaced from each other, through the side light transmission window 604; a I/O subsystem 127 for establishing data ports for data input to and data output from the PLIIM-based PIB subsystem 25''; a network controller 132, operably connected to the I/O subsystem 127 and the communication medium of the local data communication network 588; and a system control data management computer 609, operably connected to the I/O subsystem 127, for (i) receiving package identification data elements transmitted over the local data communication network by either PLIIM-based PID subsystem 25'', (ii) package dimension data elements transmitted over the local data communication network by the LDIP subsystem 122, and (iii) package weight data elements transmitted over the local data communication network by the electronic weigh scale 587. As shown, modified LDIP subsystem 122' is similar in nearly all respects to LDIP

subsystem 122, except that its beam folding mirror 167 is automatically oscillated during dimensioning in order to swept the pair of AM laser beams across the entire 3-D FOV of the side unit of the system when the product or produce item is positioned at rest upon the bottom imaging window 604. In the illustrative embodiment, the PLIIM-based camera subsystem 25'' is programmed to automatically capture images of its 3-D FOV to determine whether or not there is a stationary object positioned on the bottom imaging window 604 for dimensioning. When such an object is detected by this PLIIM-based subsystem, it either directly or indirectly automatically activates LDIP subsystem 122' to commence laser scanning operations within the 3-D FOV of the side unit and dimension the product or item of produce.

In order that the bioptical PLIIM-based PIDA system 600 is capable of capturing and analyzing color images, and thus enabling, in supermarket environments, "produce recognition" on the basis of color as well as dimensions and geometrical form, each PLIIM-based subsystem 25'' employs (i) a plurality of visible laser diodes (VLDs) having different color producing wavelengths to produce a multi-spectral planar laser illumination beam (PLIB) from the bottom and side imaging windows 604 and 605, and also (ii) a 2-D (area-type) CCD image detection array for capturing color images of objects (e.g. produce) as the objects are presented to the imaging windows of the bioptical system by the user or operator of the system (e.g. retail sales clerk).

Any one of the numerous methods of and apparatus for speckle-noise reduction described in great detail hereinabove can be embodied within the bioptical system 600 to provide an ultra-compact system capable of high performance image acquistion and processing operation, undaunted by speckle-noise patterns which seriously degrade the performance of prior art systems attempting to illuminate objects using solid-state VLD devices, as taught herein.

Notably, the image processing computer 21 within each PLIIM-based subsystem 25'' is provided with robust image processing software 610 that is designed to process color images captured by the subsystem and determine the shape/geometry, dimensions and color of scanned products in diverse retail shopping environments. In the illustrative embodiment, the IFD subsystem (i.e. "camera") 3'' within the PLIIM-based subsystem 25'' is capable of: (1) capturing digital images having (i) square pixels (i.e. 1:1 aspect ratio) independent of package height or velocity, (ii) significantly reduced speckle-noise levels, and (iii) constant image resolution measured in dots per inch (dpi) independent of package height or velocity and without the use of costly telecentric optics employed by prior art systems, (2) automatic cropping of captured images so that only regions of interest reflecting the package or package label are transmitted to either an image-processing based 1-D or 2-D bar code symbol decoder or an optical character recognition (OCR) image processor, and (3) automatic image lifting operations. Such functions are carried out in substantially the same manner as taught in connection with the tunnel-based system shown in Figs. 27 through 32B.

In most POS retail environments, the sales clerk may pass either a UPC or UPC/EAN labeled product past the bioptical system, or an item of produce (e.g. vegetables, fruits, etc.). In the case of UPC labeled products, the image processing computer 21 will decode process images

captured by the IFD subsystem 55'' (in conjuction with performing OCR processing for reading trademarks, brandnames, and other textual indicia) as the product is manually presented to the imaging windows of the system. For each product identified by the system, a product identification data element will be automatically generated and transmitted over the data communication network to the system control/management computer 609, for transmission to the host computer (e.g. cash register computer) 589 and use in check-out computations. Any dimension data captured by the LDIP subsystem 122' while identifying a UPC or UPC/EAN labeled product, can be disregarded in most instances; although, in some instances, it might make good sense that such information is automatically transmitted to the system control/management computer 609, for comparison with information in a product information database so as to cross-check that the identified product is in fact the same product indicated by the bar code symbol read by the image processing computer 21. This feature of the bioptical system can be used to increase the accurately of product identification, thereby lowering scan error rates and improving consumer confidence in POS technology.

In the case of an item of produce presented to the imaging windows of the bioptical system, the image processing computer 21 will automatically process images captured by the IFD subsystem 55'' (using the robust produce identification software mentioned above), alone or in combination with produce dimension data collected by the LDIP subsystem 122. In the preferred embodiment, produce dimension data (generated by the LDIP subsystem 122) will be used in conjunction with produce identification data (generated by the image processing computer 21), in order to enable more reliable identification of produce items, prior to weigh in on the electronic weigh scale 587, mounted beneath the bottom imaging window 604. Thus, the image processing computer 21 within the side unit 606B (embodying the LDIP subsystem') can be designated as providing primary color images for produce recognition, and cross-correlation with produce dimension data generated by the LDIP subsystem 122'. The image processing computer 21 within the bottom unit 606A (without LDIP subsystem 122') can be designated as providing secondary color images for produce recognition, independent of the analysis carried out within the side unit 606B, and produce identification data generated by the bottom unit can be transmitted to the system control/management computer 609, for cross-correlation with produce identification and dimension data generated by the side unit containing the LDIP subsystem 122'.

In alternative embodiments of the bioptical system described above, it may be desirable to use a simpler set of image forming optics than that provided within IFD subsystem 55''.

<u>PLIIM-Based Systems Employing Planar Laser Illumination Arrays With Visible Laser Diodes Having Characteristic Wavelengths Residing Within Different Portions Of The Visible Band</u>

Numerous illustrative embodiments of PLIIM-based imaging systems according to the principles of the present invention have been described in detail below. While the illustrative

embodiments described above have made reference to the use of multiple VLDs to construct each PLIA, and that the characteristic wavelength of each such VLD is substantially similar, the present invention contemplates providing a novel planar laser illumination and imaging module (PLIIM) which employs a planar laser illumination array (PLIA) 6A, 6B comprising a plurality of visible laser diodes having a plurality of different characteristic wavelengths residing within different portions of the visible band. The present invention also contemplates providing such a novel PLIIM, wherein the visible laser diodes within the PLIA thereof are spatially arranged so that the spectral components of each neighboring visible laser diode (VLD) spatially overlap and each portion of the composite planar laser illumination beam (PLIB) along its planar extent contains a spectrum of different characteristic wavelengths, thereby imparting multi-color illumination characteristics to the composite laser illumination beam. The multi-color illumination characteristics of the composite planar laser illumination beam will reduce the temporal coherence of the laser illumination sources in the PLIA, thereby reducing the speckle noise pattern produced at the image detection array of the PLIIM.

The present invention also contemplates providing a novel planar laser illumination and imaging module (PLIIM) which employs a planar laser illumination array (PLIA) comprising a plurality of visible laser diodes (VLDs) which intrinsically exhibit high "mode-hopping" spectral characteristics which cooperate on the time domain to reduce the temporal coherence of the laser illumination sources operating in the PLIA, and thereby reduce the speckle noise pattern produced at the image detection array in the PLIIM.

The present invention also contemplates providing a novel planar laser illumination and imaging module (PLIIM) which employs a planar laser illumination array (PLIA) 6A, 6B comprising a plurality of visible laser diodes (VLDs) which are "thermally-driven" to exhibit high "mode-hopping" spectral characteristics which cooperate on the time domain to reduce the temporal coherence of the laser illumination sources operating in the PLIA, and thereby reduce the speckle noise pattern produced at the image detection array in the PLIIM accordance with the principles of the present invention.

In some instances, it may also be desirable to use VLDs having characteristics outside of the visible band, such as in the ultra-violet (UV) and infra-red (IR) regions. In such cases, PLIIM-based subsystems will be produced capable of illuminating objects with planar laser illumination beams having IR and/or UV energy characteristics. Such systems can prove useful in diverse industrial environments where dimensioning and/or imaging in such regions of the electromagnetic spectrum are required or desired.

<u>Planar Laser Illumination Module (PLIM) Fabricated By Mounting A Micro-Sized Cylindrical Lens Array Upon A Linear Array Of Surface Emitting Lasers (SELs) Formed On A Semiconductor Substrate</u>

Various types of planar laser illumination modules (PLIM) have been described in detail above. In general, each PLIIM will employ a plurality of linearly arranged laser sources which

collectively produce a composite planar laser illumination beam. In certain applications, such as hand-held imaging applications, it will be desirable to construct the hand-held unit as compact and as lightweight as possible. Also, in most applications, it will be desirable to manufacture the PLIMs as inexpensively as possible.

As shown in Figs. 35A and 35B, the present invention addresses the above design criteria by providing a miniature planar laser illumination module (PLIM) on a semiconductor chip 620 that can be fabricated by aligning and mounting a micro-sized cylindrical lens array 621 upon a linear array of surface emitting lasers (SELs) 622 formed on a semiconductor substrate 623, encapsulated (i.e. encased) in a semiconductor package 624 provided with electrical pins 625, a light transmission window 626 and emitting laser emission in the direction normal to the substrate. The resulting semiconductor chip 620 is designed for installation in any of the PLIM-based systems disclosed, taught or suggested by the present disclosure, and can be driven into operation using a low-voltage DC power supply. The laser output from the PLIM semiconductor chip 620 is a planar laser illumination beam (PLIB) composed of numerous (e.g. 100-400 or more) spatially incoherent laser beams emitted from the linear array of SELs 622 in accordance with the principles of the present invention.

Preferably, the power density characteristics of the composite PLIB produced from this semiconductor chip 620 should be substantially uniform across the planar extent thereof, i.e. along the working distance of the optical system in which it is employed. If necessary, during manufacture, an additional diffractive optical element (DOE) array can be aligned upon the linear array of SELs 620 prior to placement and alignment of the cylindrical lens array 621. The function of this additional DOE array would be to spatially filter (i.e. smooth out) laser emissions produced from the SEL array so that the composite PLIB exhibits substantially uniform power density characteristics across the planar extent thereof, as required during most illumination and imaging operations. In alternative embodiments, the optional DOE array and the cylindrical lens array can be designed and manufactured as a unitary optical element adapted for placement and mounting on the SEL array 622. While holographic recording techniques can be used to manufacture such diffractive optical lens arrays, it is understood that refractive optical elements can also be used in practice with equivalent results. Also, while end user requirements will typically specify PLIB power characteristics, currently available SEL array fabrication techniques and technology will determine the realizebility of such design specifications.

In general, there are various ways of realizing the PLIIM-based semiconductor chip of the present invention, wherein surface emitting laser (SEL) diodes produce laser emission in the direction normal to the substrate.

In Fig. 36A, a first illustrative embodiment of the PLIM-based semiconductor chip 620 is shown constructed from a plurality of "45 degree mirror" (SELs) 622'. As shown, each 45 degree mirror SEL 627 of the illustrative embodiment comprises: an n-doped quarter-wave GaAs/AlAs stack 628 functioning as the lower distributed Bragg reflector (DBR); an $In_{0.2}Ga_{0.8}As/GaAs$ strained quantum well active region 629 in the center of a one-wave $Ga_{0.5}Al_{0.5}As$ spacer; and a p-doped upper GaAs/AlAs stack 630 (grown on a n+-GaAs substrate),

functioning as the top DBR; a 45 degree slanted mirror 631 (etched in the n-doped layer) for reflecting laser emission output from the active region, in a direction normal to the surface of the substrate. Isolation regions 632 are formed between each SEL 627.

As shown in Fig. 36A, a linear array of 45 degree mirror SELs are formed upon the n-doped substrate, and then a micro-sized cylindrical lens array 621 (e.g. diffractive or refractive lens array) is (i) placed upon the SEL array, (ii) aligned with respect to SEL array so that the cylindrical lens array planarizes the output PLIB, and finally (iii) permanently mounted upon the SEL array to produce the monolithic PLIM device of the present invention. As shown in Figs. 35A and 35B, the resulting assembly is then encapsulated within an IC package 624 having a light transmission window 626 through which the composite PLIB may project outwardly in direction substantially normal to the substrate, as well as connector pins 625 for connection to SEL array drive circuits described hereinabove. Preferably, the light transmission window 626 is provided with a narrowly-tuned band-pass spectral filter, permitting transmission of only the spectral components of the composite PLIB produced from the PLIM semiconductor chip.

In Fig. 36B, a second illustrative embodiment of the PLIM-based semiconductor chip is shown constructed from "grating-coupled" surface emitting laser (SELs) 635. As shown, each grating couple SEL 635 comprises: an n-doped GaAs/AlAs stack 636 functioning as the lower distributed Bragg reflector (DBR); an $In_{0.2}Ga_{0.8}As$/GaAs strained quantum well active region 637 in the center of a $Ga_{0.5}Al_{0.5}As$ spacer; and a p-doped upper GaAs/AlAs stack 638 (grown on a n+-GaAs substrate), functioning as the top DBR; and a 2nd order diffraction grating 639, formed in the p-doped layer, for coupling laser emission output from the active region, through the 2nd order grating, and in a direction normal to the surface of the substrate. Isolation regions 640 are formed between each SEL 635.

As shown in Fig. 36B, a linear array of grating-coupled SELs are formed upon the n-doped substrate, and then a micro-sized cylindrical lens array 621 (e.g. diffractive or refractive lens array) is (i) placed upon the SEL array, (ii) aligned with respect to SEL array so that the cylindrical lens array planarizes the output PLIB, and finally (iii) permanently mounted upon the SEL array to produce the monolithic PLIM device of the present invention. As shown in Figs. 35A and 35B, the resulting assembly is then encapsulated within an IC package having a light transmission window 626 through which the composite PLIB may project outwardly in direction substantially normal to the substrate, as well as connector pins 625 for connection to SEL array drive circuits described hereinabove. Preferably, the light transmission window 626 is provided with a narrowly-tuned band-pass spectral filter, permitting transmission of only the spectral components of the composite PLIB produced from the PLIM semiconductor chip.

In Fig. 36C, a third illustrative embodiment of the PLIIM-based semiconductor chip 620 is shown constructed from "vertical cavity" (SELs), or VCSELs. As shown, each VCSEL comprises: an n-doped quarter-wave GaAs/AlAs stack 646 functioning as the lower distributed Bragg reflector (DBR); an $In_{0.2}Ga_{0.8}As$/GaAs strained quantum well active region 647 in the center of a one-wave $Ga_{0.5}Al_{0.5}As$ spacer; and a p-doped upper GaAs/AlAs stack 648 (grown on a n+-GaAs substrate), functioning as the top DBR, with the topmost layer is a half-wave-thick

GaAs layer to provide phase matching for the metal contact; wherein laser emission from the active region is directed in opposite directions, normal to the surface of the substrate. Isolation regions 649 are provided between each VCSEL 645.

As shown in Fig. 36C, a linear array of VCSELs are formed upon the n-doped substrate, and then a micro-sized cylindrical lens array 621 (e.g. diffractive or refractive lens array) is (i) placed upon the SEL array, (ii) aligned with respect to SEL array so that the cylindrical lens array planarizes the output PLIB, and finally (iii) permanently mounted upon the SEL array to produce the monolithic PLIM device of the present invention. As shown in Figs. 35A and 35B, the resulting assembly is then encapsulated within an IC package having a light transmission window 626 through which the composite PLIB may project outwardly in direction substantially normal to the substrate, as well as connector pins 625 for connection to SEL array drive circuits described hereinabove. Preferably, the light transmission window 626 is provided with a narrowly-tuned band-pass spectral filter, permitting transmission of only the spectral components of the composite PLIB produced from the PLIM semiconductor chip.

Each of the illustrative embodiments of the PLIIM semiconductor chip described above can be constructed using conventional VCSEL array fabricating techniques well known in the art. Such methods may include, for example, slicing a SEL-type visible laser diode (VLD) wafer into linear VLD strips of numerous (e.g. 200-400) VLDs. Thereafter, a cylindrical lens array 621, made using from light diffractive or refractive optical material, is placed upon and spatially aligned with respect to the top of each VLD strip 622 for permanent mounting, and subsequent packaging within an IC package 624 having an elongated light transmission window 626 and electrical connector pins 625, as shown in Figs. 35A and 35B. For details on such SEL array fabrication techniques, reference can be made to pages 368-413 in the textbook "Laser Diode Arrays" (1994), edited by Dan Botez and Don R. Scifres, and published by Cambridge University Press, under Cambridge Studies in Modern Optics, incorporated herein by reference.

Notably, each SEL in the laser diode array can be designed to emit coherent radiation at a different characteristic wavelengths to produce an array of coplanar laser illumination beams which are substantially temporally and spatially incoherent with respect to each other. This will result in producing from the PLIM semiconductor chip, a temporally and spatially coherent-reduced planar laser illumination beam (PLIB), capable of illuminating objects and producing digital images having substantially reduced speckle-noise patterns observable at the image detection array of the PLIIM-based system in which the PLIM chip is used (i.e. when used in accordance with the principles of the invention taught herein).

The PLIM semiconductor chip of the present invention can be made to illuminate outside of the visible portion of the electromagnetic spectrum (e.g. over the UV and/or IR portion of the spectrum). Also, the PLIM semiconductor chip of the present invention can be modified to embody laser mode-locking principles, shown in Figs. 1I15C and 1I15D and described in detail above, so that the PLIB transmitted from the chip is temporally-modulated at a sufficient high rate so as to produce ultra-short planes light ensuring substantial levels of speckle-noise pattern reduction during object illumination and imaging applications.

One of the primary advantages of the PLIM-based semiconductor chip of the present invention is that by providing a large number of VCSELs (i.e. real laser sources) on a semiconductor chip beneath a cylindrical lens array, speckle-noise pattern levels can be substantially reduced by an amount proportional to the square root of the number of independent laser sources (real or virtual) employed.

Another advantage of the PLIM-based semiconductor chip of the present invention is that it does not require any mechanical parts or components to produce a spatially and/or temporally coherence-reduced PLIB during system operation.

Also, during manufacture of the PLIM-based semiconductor chip of the present invention, the cylindrical lens array and the VCSEL array can be accurately aligned using substantially the same techniques applied in state-of-the-art photo-lithographic IC manufacturing processes. Also, de-smiling of the output PLIB can be easily corrected during manufacture by simply rotating the cylindrical lens array in front of the VLD strip.

Notably, one or more PLIM-based semiconductor chips of the present invention can be employed in any of the PLIIM-based systems disclosed, taught or suggested herein. Also, it is expected that the PLIM-based semiconductor chip of the present invention will find utility in diverse types of instruments and devices, and diverse fields of technical application.

<u>Planar Laser Illumination And Imaging Module (PLIIM) Fabricated By Mounting A Pair Of Micro-Sized Cylindrical Lens Arrays Upon A Pair Of Linear Arrays Of Surface Emitting Lasers (SELs) Formed Between A Linear CCD Image Detection Array On A Common Semiconductor Substrate</u>

As shown in Fig. 37, the present invention further contemplates providing a novel planar laser illumination and imaging module (PLIIM) 650 realized on a semiconductor chip. As shown in Fig. 36, a pair of micro-sized (diffractive or refractive) cylindrical lens arrays 651A and 651B are mounted upon a pair of large linear arrays of surface emitting lasers (SELs) 652A and 652B fabricated on opposite sides of a linear CCD image detection array 653. Preferably, both the linear CCD image detection array 653 and linear SEL arrays 652A and 652B are formed a common semiconductor substrate 654, and encased within an integrated circuit package 655 having electrical connector pins 656, a first and second elongated light transmission windows 657A and 657B disposed over the SEL arrays 652A and 652B, respectively, and a third light transmission window 658 disposed over the linear CCD image detection array 653. Notably, SEL arrays 652A and 652B and linear CCD image detection array 653 must be arranged in optical isolation of each other to avoid light leaking onto the CCD image detector from within the IC package. When so configured, the PLIIM semiconductor chip 650 of the present invention produces a composite planar laser illumination beam (PLIB) composed of numerous (e.g. 400-700) spatially incoherent laser beams, aligned substantially within the planar field of view (FOV) provided by the linear CCD image detection array, in accordance with the principles of the present invention. This PLIIM-based semiconductor chip is powered by a low voltage/low

power P.C. supply and can be used in any of the PLIIM-based systems and devices described above. In particular, this PLIIM-based semiconductor chip can be mounted on a mechanically oscillating scanning element in order to sweep both the FOV and coplanar PLIB through a 3-D volume of space in which objects bearing bar code and other machine-readable indicia may pass. This imaging arrangement can be adapted for use in diverse application environments.

<u>Planar Laser Illumination And Imaging Module (PLIIM) Fabricated By Forming A 2D Array Of Surface Emitting Lasers (SELs) About A 2D Area-Type CCD Image Detection Array On A Common Semiconductor Substrate, With A Field of View Defining Lens Element Mounted Over The 2D CCD Image Detection Array and A 2D Array of Cylindrical Lens Elements Mounted Over The 2D Array of SELs</u>

A shown in Figs. 38A and 38B, the present invention also contemplates providing a novel 2D PLIIM-based semiconductor chip 360 embodying a plurality of linear SEL arrays 361A, 361B..., 361n..., which are electronically-activated to electro-optically scan (i.e. illuminate) the entire 3-D FOV of a CCD image detection array 362 without using mechanical scanning mechanisms. As shown in Fig. 38B, the miniature 2D VLD/CCD camera 360 of the illustrative embodiment can be realized by fabricating a 2-D array of SEL diodes 361 about a centrally located 2-D area-type CCD image detection array 362, both on a semiconductor substrate 363 and encapsulated within a IC package 364 having connection pins 364, a centrally-located light transmission window 365 positioned over the CCD image detection array 362, and a peripheral light transmission window 366 positioned over the surrounding 2-D array of SEL diodes 361. As shown in Fig. 38B, a light focusing lens element 367 is aligned with and mounted beneath the centrally-located light transmission window 365 to define a 3D field of view (FOV) for forming images on the 2-D image detection array 362, whereas a 2-D array of cylindrical lens elements 368 is aligned with and mounted beneath the peripheral light transmission window 366 to substantially planarize the laser emission from the linear SEL arrays (comprising the 2-D SEL array 361) during operation. In the illustrative embodiment, each cylindrical lens element 368 is spatially aligned with a row (or column) in the 2-D SEL array 361. Each linear array of SELs 361n in the 2-D SEL array 361, over which a cylindrical lens element 366n is mounted, is electrically addressable (i.e. activateable) by laser diode control and drive circuits 369 which can be fabricated on the same semiconductor substrate. This way, as each linear SEL array is activated, a PLIB 370 is produced therefrom which is coplanar with a cross-sectional portion of the 3-D FOV 371 of the 2-D CCD image detection array. To ensure that laser light produced from the SEL array does not leak onto the CCD image detection array 362, a light buffering (isolation) structure 372 is mounted about the CCD array 362, and optically isolates the CCD array 362 from the SEL array 361 from within the IC package 364 of the PLIIM chip 360.

The novel optical arrangement shown in Figs. 3A and 3B enables the illumination of an object residing within the 3D FOV during illumination operations, and formation of an image strip on the corresponding rows (or columns) of detector elements in the CCD array. Notably,

beneath each cylindrical lens element 366n (within the 2-D cylindrical lens array 366), there can be provided another optical surface (structure) which functions to widen slightly the geometrical characteristics of the generated PLIB, thereby causing the laser beams constituting the PLIB to diverge slightly as the PLIB travels away from the chip package, ensuring that all regions of the 3D FOV 371 are illuminated with laser illumination, understandably at the expense of a decrease beam power density. Preferably, in this particular embodiment of the present invention, the 2-D cylindrical lens array 366 and FOV-defining optical focusing element 367 are fabricated on the same (plastic) substrate, and designed to produce laser illumination beams having geometrical and optical characteristics that provide optimum illumination coverage while satisfying illumination power requirements to ensuring that the signal-to-noise (SNR) at the CCD image detector 362 is sufficient for the application at hand.

One of the primary advantages of the PLIIM-based semiconductor chip design 360 shown in Figs. 38A and 38B is that its linear SEL arrays 361n can be electronically-activated in order to electro-optically illuminate (i.e. scan) the entire 3-D FOV 371 of the CCD image detection array 362 without using mechanical scanning mechanisms. In addition to the providing a miniature 2D CCD camera with an integrated laser-based illumination system, this novel semiconductor chip 360 also has ultra-low power requirements and packaging constraints enabling its embodiment within diverse types of objects such, as for example, appliances, keychains, pens, wallets, watches, keyboards, portable bar code scanners, stationary bar code scanners, OCR devices, industrial machinery, medical instrumentation, office equipment, hospital equipment, robotic machinery, retail-based systems, and the like. Applications for PLIIM-based semiconductor chip 360 will only be limited by ones imagination. The SELs in the device may be provided with multi-wavelength characteristics, as well as tuned to operate outside the visible region of the electromagnetic spectrum (e.g. within the IR and UV bands). Also, the present invention contemplates embodying any of the speckle-noise pattern reduction techniques disclosed herein to enable its use in demanding applications where speckle-noise is intolerable. Preferably, the mode-locking techniques taught herein may be embodied within the PLIIM-based semiconductor chip 360 shown in Figs. 38A and 38B so that it generates and repeated scans temporally coherent-reduced PLIBs over the 3D FOV of its CCD image detection array 362.

Fields of Application: Modifications Of The Illustrative Embodiments

While each embodiment of the PLIIM system of the present invention disclosed herein has employed a pair of planar laser illumination arrays, it is understood that in other embodiments of the present invention, only a single PLIA may be used, whereas in other embodiments three or more PLIAs may be used depending on the application at hand.

While the illustrative embodiments disclosed herein have employed electronic-type imaging detectors (e.g. 1-D and 2-D CCD-type image sensing/detecting arrays) for the clear advantages that such devices provide in bar code and other photo-electronic scanning

applications, it is understood, however, that photo-optical and/or photo-chemical image detectors/sensors (e.g. optical film) can be used to practice the principles of the present invention disclosed herein.

While the package conveyor subsystems employed in the illustrative embodiments have utilized belt or roller structures to transport packages, it is understood that this subsystem can be realized in many ways, for example: using trains running on tracks passing through the laser scanning tunnel; mobile transport units running through the scanning tunnel installed in a factory environment; robotically-controlled platforms or carriages supporting packages, parcels or other bar coded objects, moving through a laser scanning tunnel subsystem.

Expectedly, the PLIIM-based systems disclosed herein will find many useful applications in diverse technical fields. Examples of such applications include, but are not limited to: automated plastic classification systems; automated road surface analysis systems; rut measurement systems; wood inspection systems; high speed 3D laser profing sensors; stereoscopic vision systems; stroboscopic vision systems; food handling equipment; food harvesting equipment (harvesters); optical food sortation equipment; etc.

The various embodiments of the package identification and measuring system hereof have been described in connection with scanning linear (1-D) and 2-D code symbols, graphical images as practiced in the graphical scanning arts, as well as alphanumeric characters (e.g. textual information) in optical character recognition (OCR) applications. Examples of OCR applications are taught in US Patent No. 5,727,081 to Burges, et al, incorporated herein by reference.

It is understood that the systems, modules, devices and subsystems of the illustrative embodiments may be modified in a variety of ways which will become readily apparent to those skilled in the art, and having the benefit of the novel teachings disclosed herein. All such modifications and variations of the illustrative embodiments thereof shall be deemed to be within the scope and spirit of the present invention as defined by the Claims to Invention appended hereto.